



**Developing Methodologies for Sustainable Groundwater
Management in sub-Saharan Africa: a case study of the Chad Basin
around Maiduguri, Nigeria**

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ABSTRACT

This study developed sustainable groundwater management methodology applicable to sedimentary environments in sub-Saharan Africa, taking the Chad basin, North-eastern Nigeria as a case study. The study employed integrated methodological approaches and is divided into three major interrelated phases. The first phase of the study carried out a stakeholder analysis and identified the stakeholders that are responsible for and those affected by problems of groundwater contamination as well as those that have formal authority and influence in addressing the situation. A total of 22 stakeholder groups comprised of; 10 government agencies, 4 water user groups, 3 professional organisations, 3 civil society organisations, an NGO, and a research institution were identified and engaged at the tactical level via interviews, focus groups, and household surveys. The second phase evaluated the various above ground pollution sources and assessed their impact on groundwater, and carried out physico-chemical investigation of groundwater samples collected from selected shallow boreholes across the study area in determining the extent of contamination from the aforesaid pollution sources. The third phase of the study carried out modelling of chloride contamination due to pit latrine impacts and developed guidelines for mitigating the negative impact of on-site sanitation systems on the underlying aquifer. The results of the stakeholder engagement show that knowledge about groundwater contamination is good among the strategic stakeholders and limited among the primary stakeholders. Also, most interviewees are concerned about problems of contamination and are keen to be part of addressing the situation, a handful of focus group participants, and the survey respondents are equally concerned about this issue. Also, all the stakeholder categories suggested that community participation, increase in investment, controlling waste from source, and strict legislations are the possible ways of addressing the existing problems of groundwater management in the study area. Overall, social, economic, and cultural influences are the factors responsible for the prevalence of the pit latrines and open dumpsites. Risk matrix result shows that pit latrines, dumpsites, and other non-point sources are the potential sources of pollution based on the order of their magnitude. Geological material constitutes the lowest risks. Groundwater Physico-chemical analyses result show that the groundwater in the study area ranged from alkaline (pH 6.61-7.57) to slightly alkaline-acidic (6.2-7.31). The distribution of non-anthropogenic parameters such as; Na^{2+} , Ca^{2+} , K^{+} , and Mg^{2+} across all the boreholes varied significantly ($p < 0.05$; significant level of 95% and confidence interval of 0.05). Also, the concentrations of anthropogenic indicator parameters such as; Cl^{-} , NO_3^{-} , SO_4^{2-} , and PO_4^{3-} in the groundwater are correlated with the above ground pollution sources; their distribution across the boreholes of the study area varied significantly ($p < 0.05$). Furthermore, the groundwater is currently of good quality for consumption. Equally, Granulometric and mineral content analyses of the sediment were carried out to determine the sediments particle sizes and the distribution of their contained minerals. Results show that the sediments particles ranged between 1mm-<63 μm while minerals such as Quartz, Feldspar, Albite, Zircon and Iron Oxide are dominant. The alternative guidelines developed by this study can be applied across the major sedimentary basins of Nigeria. The study provides baseline data for achieving sustainable groundwater management in sub-Saharan Africa region. The concept outlined in this thesis can be replicated in other international case studies across Africa.

DEDICATION

*To my Late Daughter
Fatima Ali (Ummul-Khair)
Of Blessed Memory*

AUTHOR'S DECLARATION

By the Candidate:

I **ALI BAKARI MOHAMMED** declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy at the Abertay University, Dundee, United Kingdom. It has not been submitted before for any degree or examination in any other University.

Signed:

By the supervisors:

It is hereby declared that the work presented in this Thesis is the work of the candidate ALI BAKARI MOHAMMED, and that in carrying out this work, the conditions of the relevant Ordinance and Regulations have been fulfilled.

Signed:

Professor Joseph Akunna

Professor David Blackwood

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ACRONYMS AND ABBREVIATIONS

AICD	Africa Infrastructure Country Diagnostic
BGS	British Geological Survey
BHG	Borehole in Gwange
BHM	Borehole in Moduganari
BOHA	Borno State House of Assembly
BOSEPA	Borno State Environment Protection Agency
BOSG	Borno State Government
CSO	Civil Society Organisation
DEFRA	Department for Environment Food and Rural Affairs
EC	Electrical Conductivity
EC	European Commission
ECOWAS	Economic Community of West African States
EEA	European Economic Area
EEC	European Economic Council
ESRI	Environmental Systems Research Institute
EU	European Union
FG	Focus Group
FGN	Federal Government of Nigeria
FMWR	Federal Ministry of Water Resources
GBR	General Binding Rules
GDQW	Guidelines for Drinking Water Quality
GIS	Geographic Information System
GPS	Global Positioning System
HOD	Head of Department
IAH	International Association of Hydrogeologists
IAHS	International Hydrological Society
IWRM	Integrated Water Resources Management

LA	Learning Alliances
LCBC	Lake Chad Basin Commission
LGA	Local Government Area
MDGs	Millennium Development Goals
MMC	Maiduguri Metropolitan Council
NBS	Nigeria Bureau of Statistics
NGO	Non-Governmental Organisation
NGWA	National Groundwater Association
NPC	National Population Commission
NUJ	Nigeria Union of Journalists
NUT	Nigeria Union of Teachers
RBDA	River Basin Development Agency
RGS	Royal Geographical Society
SDGs	Sustainable Development Goals
SEPA	Scottish Environment Protection Agency
SNM	Strategic Niche Management
SSA	Sub-Saharan Africa
SWA	State Water Agency
TDS	Total Dissolved Solids
UK	United Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNICEF	United Nations International Children Endowment Fund
USA	United States of America
USAID	United States Aid Agency
USD	United States Dollars
USEPA	United States Environment Protection Agency
USGS	United States Geological Survey

WACDEP	Water Climate and Development
WASH	Water Sanitation and Hygiene
WFD	Water Framework Directives
WHO	World Health Organisation

Table of Contents

Abstract.....	li
Dedication.....	lii
Author's Declaration.....	lv
AUD-Permission to Copy.....	V
Acronyms and Abbreviations.....	Vi
List of Figures.....	Xvi
List of Tables.....	Xvii
AUTHOR'S DECLARATION	iv
Major research output	xx
CHAPTER 1	1
GENERAL INTRODUCTION	1
1.1 Background	1
1.2 Justification for the study and rationale for a case study.....	8
1.3 Aim and objectives.....	16
1.4 Research questions	17
1.5 Methodology.....	18
1.6 Structure of the thesis	19
1.7 Scope and limitations of the study	21
1.8 Summary and conclusion	22
CHAPTER 2	23
ASPECTS OF GROUNDWATER CONTAMINATION, MANAGEMENT, & UTILISATION IN SUB-SAHARAN AFRICA.....	23
2. Introduction.....	23
2.1 Groundwater.....	24
2.2 Characteristics of hydrogeological environment in sub-Saharan Africa.....	26
2.2.1. Hydrogeological environment solid phase.....	28

2.2.2 Hydrogeological environment Liquid Phase	29
2.2.3 Hydrogeological environment Gaseous Phase	30
2.3 Types of Contamination processes occurring in the Sedimentary Environment	31
2.4 Groundwater quality standards in sub-Saharan Africa region	35
2.5 Groundwater sampling strategies and protocols	37
2.6 Groundwater Management and Utilisation in Africa	38
2.6.1 Groundwater Management and Utilisation in the West African Sub-region	39
2.6.2 Groundwater Management and Utilisation in the Southern Africa Region	40
2.6.3 Groundwater Management and Utilisation in Eastern Africa Region	40
2.7 Groundwater contaminants and contamination issues in sub-Saharan Africa	42
2.8 Groundwater Sustainability in Sub-Saharan Africa.....	46
2.8.1 Sustainability-based Approaches for Groundwater Management.....	47
2.9 Research Philosophy and Epistemology	57
2.9.1 Questionnaire design and developing the research questions.....	60
2.9.2 Hypothesis testing.....	62
2.10 Summary and conclusion	63
CHAPTER 3	67
CASE STUDY AREA.....	67
3. Introduction.....	67
3.1 The Study Area	67
3.2 Demography.....	69
3.3 Climate and Vegetation	70
3.4 Relief and Drainage.....	72
3.5 Geology and Hydrogeology of the Study Area.....	73
3.6 Status of Water Supply Provisions in Maiduguri Metropolis	79

3.7	Environmental Problems in Maiduguri Metropolis	79
3.8	Potential Sources of pollution in Maiduguri	80
3.8.1	Open Dumpsites	82
3.8.2	Pit Latrines and Septic Tanks	83
3.8.3	Cattle Markets and Abattoirs	84
3.8.4	Agricultural Activities	84
3.8	Other Potential Sources of Groundwater Pollution.....	86
3.9	Pollution Sources Risk Assessment	87
3.10	Summary and conclusion	88
CHAPTER 4	91
METHODOLOGY	91
4. Introduction	91
4.1	Quantitative strategy: groundwater quality analytical methods	92
4.1.1	Reconnaissance Survey	92
4.1.2	Pollution Sources Identification	93
4.1.3	Selection of Groundwater Sampling Sites.....	94
4.1.4	Experimental approach.....	97
4.1.5	Sediment Sample Collection	103
4.1.6	Hydrogeological Model Data	104
4.2	Qualitative Strategy: a Social Dimension	107
4.2.1	Stakeholder Analysis	107
4.2.2	Interviews	110
4.2.3	Pre-focus Group Capacity Building Workshops	112
4.2.4	Focus Group Discussions	113
4.2.5	Household Survey	116
4.3	Methods of Data Analysis	119
4.3.1	Thematic Analysis Procedure	120

4.3.2 Axial Coding	121
4.3.3 Statistical analysis methods	122
The study has adopted the following statistical analyses:	122
4.4 Methodology for developing the alternative guidelines	128
4.5 Summary and conclusions	132
CHAPTER 5	134
STAKEHOLDER ENGAGEMENT & HYDROGEOLOGICAL RESULTS	134
5. Introduction	134
5.1 Results from the Strategic Stakeholders Engagement.....	134
5.1.1 Opinions from the Semi-structured Interviews with the Strategic Stakeholders across the various Ministries and Organisations in Maiduguri	135
5.2 Stakeholders opinion from the various Focus Group Discussions.....	138
5.2.1 Knowledge about Groundwater Contamination	139
5.2.2 Concerns about Groundwater Contamination.....	140
5.2.3 Common Causes of Groundwater Contamination	140
5.2.4 Waste Generation	141
5.2.5 Waste Disposal.....	141
5.3 Environmental Problems.....	143
5.3.1 Knowledge about Groundwater Contamination	143
5.3.2 Concerns about Groundwater Contamination.....	143
5.3.3 Common Causes of Groundwater Contamination	144
5.3.5 Waste Disposal.....	145
5.4 Socio-demographic characteristics of the households surveyed in the study area	146
5.4.1 Sex of Respondents	146
5.4.2 Marital Status.....	146
5.4.3 Age of the Respondents.....	146
5.4.4 Educational attainment of the respondents	147
5.4.5 Income of the households surveyed	147

5.4.6 Employment status of Respondents	147
5.4.7 Household size	148
5.4.8 Common causes of groundwater contamination.....	150
5.4.9 Wastes generation and collection	150
5.4.10 Waste disposal method.....	151
5.4.11 Willingness to pay for improved sanitation services	152
5.4.12 Household's awareness level on groundwater contamination.....	153
5.4.13 Distribution of Awareness about the implications of dumping waste by sex and educational level	154
5.4.14 Distribution of population growth concerns and urban growth concerns by age	156
5.4.15 Distribution of population growth concerns and urban growth concerns by educational level	157
5.4.16 Sustainable options for achieving sustainable groundwater management.....	158
5.5. Hydrogeological Dimension	159
5.5.1 Site Description for Hydrogeological Assessment	159
5.5.2 Pollution Pathways in Maiduguri.....	160
5.6 Pathway Mineralogical Composition Analyses Results.....	164
5.7 The Groundwater System	168
5.7.1 Groundwater Quality.....	169
5.8 Discussions	177
5.8.1 Discussion of social aspects.....	177
5.8.2 Discussion on hydrogeological aspects	184
5.9 Summary and conclusions	189
CHAPTER 6	196
MODELLING CHLORIDE CONTAMINATION AND NEW GUIDELINE DEVELOPMENT	196
6. Introduction	196
6.1 Modelling chloride contamination due to pit latrine impact	197
6.1.1 Modelling approach	199

6.2 Follow-up (household) survey data used for developing the new guidelines	205
6.3 Establishing Sustainable Guidelines for Unconsolidated Sediment Hydrogeological Environment	207
6.3.1 Mitigation Framework for Unconsolidated Sediment Hydrogeological Environment	210
6.4 Guidelines for the Maintenance and Operation of Existing On-site Sanitation Systems	215
6.4.1 Operation and Maintenance Guidelines for Existing Pit latrines	215
6.4.2 Operation and maintenance guidelines for existing open dumpsites.....	218
6.5 Discussions	220
6.5.1 Chloride modelling.....	220
6.5.2 Follow-up survey and new guidelines development	227
6.6 Summary and conclusion	230
CHAPTER 7	233
CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORK	233
7. Introduction	233
7.1 Conclusions	233
7.2 Policy Recommendations for Attaining a Viable groundwater System in Sub-Saharan Africa.	239
7.2.1 Educating the Citizenry on Groundwater Protection	240
7.2.2 Provision of Adequate Legislation for Participatory Water Management.....	240
7.2.3 Waste Management.....	241
7.2.4 Institutional Integration and Streamlining of Responsibilities	241
7.2.5 Additional Commitment by the Various Tiers of Government	242
7.3 Recommendations for Future Research	243
References	245

Figure	List of figures	Page
1.1	Map of Africa showing the study area and major climatic belts	4
1.2	Regional Geology of the Chad Basin showing the aquifer systems	5
1.3	Map of Africa showing the population distribution	6
1.4	Conceptual representation showing River-aquifer connectivity	7
1.5	Residential and commercial waste disposed in River Ngadda	8
1.6	socio-hydrogeology outline	11
1.7	Research Outline	14
2.1	A cross section showing groundwater distribution	24
2.2	Hydrogeological cycle describing groundwater origin	25
2.3	Sub-surface liquid phase configuration	30
2.4	Darcy's experimental set up	52
3.1	Map of Nigeria showing Maiduguri, Borno state	69
3.2	Map of Africa showing annual population growth rate	70
3.3	Typical Sudano-sahel vegetation	73
3.4	Model showing relief across the Nigerian sector of the Chad Basin	74
3.5	Cross section of the multi-layered aquifer system in Maiduguri	75
3.6	Cross section showing upper, middle and lower aquifer	77
3.7	Incessant solid waste disposals in residential area in Maiduguri	83
3.8	One of the open dumpsites in Gwange area in Maiduguri	84
3.9	Irrigation farming in the Alau Dam area in Maiduguri	86
4.1	Map showing extent of Maiduguri metropolis	93
4.2	Aerial view of Moduganari area showing concentration of pit latrines and open dump sites	94
4.3	Map of the study area showing the different sampling location	96
4.4	Some of the groundwater samples obtained for Hydrochemical analyses	99
4.5	2D cross section (B-B') showing boreholes 9, 8, and 7 in Moduganari area	106
4.6	3D Conceptual representation of the upper aquifer in Maiduguri	107
4.7	Interview with some of the strategic stakeholders	112
4.8	Pre-focus group capacity building workshop in the case study area	115

4.9	Focus group discussions with some participants in the case study area	117
4.10	The researcher sorting out the filled household survey questionnaires	119
5.1	Stakeholder concerns about groundwater contamination	138
5.2	Most preferred waste disposal methods	151
5.3	Households awareness about groundwater contamination	153
5.4	Households views on achieving sustainable groundwater management	159
5.5	Strip logs of selected boreholes in Moduganari area showing	160
5.6	the local geology and aquifer	161
5.7	Grain Morphology analyses for Moduganari area (site 1)	162
5.8	Strip logs of selected boreholes in Gwange area showing	163
	the local geology and aquifer	
5.9	Grain Morphology analyses for Gwange area (site 2)	168
5.10	Conceptual representation of the upper aquifer in Gwange area	169
5.11	Conceptual representation of the upper aquifer in Moduganari area	171
5.12	Concentration of cation in groundwater samples of Moduganari (site 1)	172
5.13	Trilinear plot showing concentration of cations and anions in two boreholes of sites 1 and 2.	173
5.14	Cross section (D-D') showing boreholes 9 and 3 including their constituents' time series and radial diagram in Gwange area	173
5.15	Concentration of anthropogenic indicator parameters in Gwange (site 2)	176
	Cross section (C-C') showing profile of boreholes 7 and 8	178
5.16	including their constituents (anions) in Gwange area	178
6.1	Conceptual model showing pit latrine impacts	198
6.2	Schematic description of the model input parameters	202
6.3	Range of chloride concentrations over different periods	204
6.4	Percentage distribution of pit latrine depths	216
6.5	Steps for developing the guidelines for mitigating the impact of on-site sanitation systems in groundwater	220
6.6	Conceptual model for mitigating anthropogenic impact in unconsolidated sediments	222

Tables	List of tables	Page
2.1	Summary of the major hydrogeological environments and their composition in sub-Saharan Africa	27
2.2	Summary of primary and secondary minerals	29
2.3	Summary of regional groundwater management institutions and legislation in sub-Saharan Africa region	42
2.4	Summary of groundwater contamination problems	43
2.5	Potential contaminants and their associated health issues	44
2.6	Case study Method: Strength Vs Weaknesses	60
3.1	Population distribution by category in Nigeria	71
3.2	Representation of Borehole log showing upper, middle and lower aquifers in Maiduguri	78
3.3	Summary of potential risks and contaminant types	82
3.4	Ranking of pollution sources based on risk matrix result	89
4.1	Summary of borehole location in the two sampling sites	97
4.2	Summary of equipment error levels	98
4.3	Summary of chemical analyses employed in the study	103
4.4	Summary of data requirement for EnvironInsite hydroanalysis	106
4.5	Stakeholder Categorisation as primary, secondary and key	110
4.6	Summary of the various stakeholder groups in the study area	110
4.7	Summary of stakeholders interviewed and their affiliations	112
5.1	Opinions from axial coding of stakeholder interviews	134
5.2	Opinions from the axial coding of the 3 focus groups workshops in site 1	139
5.3	Opinions from the axial coding of the 3 focus groups workshops in site 2	142
5.4	Summary of socio-economic characteristics of households	149
5.5	Summary of test statistics of households willingness to pay	152
5.6	Summary of test statistics for level of education and awareness level of respondents	155
5.7	Summary of test statistics for educational status and awareness about dumping	156
5.8	Modal Composition results for site 1	164
5.9	Modal Composition results for site 2	165
5.10	Summary of particle size distribution (%) at the depth of 5m	166
5.11	Summary of particle size distribution (%) at the depth of 10m	166
5.12	Summary of grain morphology results at the depth of 5m	167
5.13	Summary of grain morphology results at the depth of 10m	167
5.14	Summary of mineral composition of sediments obtained at 5 and 10 meters depth	167
5.15	Comparison of groundwater physico-chemical quality result	174

5.16	Chemical parameters mean values for site 1	175
5.17	Chemical parameters mean value for site 2	175
5.18	Summary of key points opined by stakeholders	191
6.1	Summary of model simulation results	203
6.2	Summary of household survey data	217
6.3	Summary of key outcomes of foregoing chapters	219
6.4	Best management practices for unconsolidated sediments	224
6.5	Comparison of the design parameters to established standards	226
6.6	Proposed guidelines for mitigating impact of existing pit latrines and the stakeholders involved	229
6.7	Proposed guidelines for mitigating impacts of existing dump sites and the stakeholders involved	232

Major research output

- Bakari, A. (2016). Transitioning to Sustainable Groundwater Management in Nigeria. In: Vogwill, R. Solving the Groundwater Challenges of the 21st Century; IAH Green Book Series, CRC Press. ISBN 9781138027473.
- Bakari, A., Akunna, J. C., & Jefferies, C. (2014). Towards sustainable groundwater management in the south-western part of the Chad Basin, Nigeria: a stakeholder perspective. *British Journal of Applied Science & Technology* 4 (25).
- Bakari, A. (2014). Hydrochemical assessment of groundwater quality in the Chad Basin around Maiduguri, Nigeria. *Journal of Geology and Mining Research*, 6(1), 1-12.
- Bakari, A. (2014). An investigation of the physical and mineralogical characteristics of the quaternary formation of the Chad Basin, Nigeria. *International Journal of Scientific & Technology Research* 3 (8).
- Bakari, A., and Jefferies, C. (2013) Transitioning to Sustainable Groundwater Management in Maiduguri, Nigeria. Paper presented at the 40th World Congress of the International Association of Hydrogeologists (IAH), Perth, Western Australia, 15-20 September 2013.

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

Groundwater plays an increasingly significant role in domestic, industrial and agricultural water supply in Sub-Saharan Africa region. It is estimated that 2 billion people worldwide depend on groundwater for drinking water (Salman, 1999; IAH, 2006; Gleeson et al., 2012). The annual global groundwater extraction increased in recent decades from 100 km³ a year in 1950 to a current estimated use of about 800 km³ a year (Schlager, 2007; Wada et al., 2010). Today, 43 percent of global irrigation (Giordano and Villholth, 2007; Siebert et al., 2010) as well as more than 50 percent of the world's drinking water supply (Zekster and Everett, 2004) and a large share of global industrial activity depend on groundwater (World Bank, 2010; GWP, 2012).

In Nigeria and most parts of sub-Saharan Africa (especially the Sudano-sahel region), groundwater plays a vital role in the development of urban and rural areas. In a recent report, the British Geological Survey estimated that the groundwater potentials of aquifers in Africa are 100 times the amount found on the surface (MacDonald et al., 2011; McGrath, 2012). Currently, more than half of the continent's populations depend directly on this natural resource for their daily water needs. In Nigeria and the entire sub-continent, the provision of safe drinking water especially in

the rural areas has deteriorated; access in urban areas fell from 80 per cent to 76 per cent in the last decade alone (AICD, 2011). This is largely due to poor management; inadequate technical capabilities and human capacities, insufficient investment and funding. Others are lack of stakeholder participation in the management of groundwater resources and the fragmented nature of national institutions responsible for water management (Jacobsen et al., 2012). The stated problems above, were the reasons for non-attainment of the Millennium Development Goals (MDG), if not well addressed, it will make the fulfillment of Sustainable Development Goals (SDG) difficult in the sub-continent.

Additionally, rapid population growth and uncontrolled urbanisation further aggravate the increasing magnitude and distribution of above ground human activities that potentially affect the quality and quantity of the underlying groundwater in this region (Foster et al., 1998). Uncontrolled urbanisation, high population densities and the ever increasing human activities all severely affect groundwater quality in this region. Thus, this study aims to address the above-mentioned problems with special emphasis on the Sudano-sahel region of sub-Saharan Africa (see figures 1.1, 1.2a and 1.3).

The Sudano-sahel region covers most parts of west Africa; it spans across northern Senegal, southern Mauritania, central Mali, northern Burkina Faso, extreme south of Algeria, Niger Republic, extreme north of Nigeria, central Chad, central and southern Sudan, and some parts of northern Eritrea (Dai et al., 2004). The

justification for the selection of this region is because it is one of the most water stressed region in Africa (Figure 1.1), and it is grossly affected by environmental problems attributed to above ground anthropogenic activities (AICD, 2011). Secondly, another important factor that led to the selection of this case study area is because of its socio-economic significance in sub-Saharan Africa region; it serves as the commercial gateway of the entire Sahel region (area with the highest anthropogenic pressure due to economic activities) hence, it is an excellent representative of the regional generic problems attributed to socio-demographic impacts across Africa.

This sub-region was chosen to provide insights into the broader problem of groundwater contamination across sub-Saharan Africa region. Also, geological and socio-economic characteristics are the key parameters that guided the selection of the case study area. Geologically, the Chad Basin is the largest sedimentary Basin in the region with relatively uniform geology (Figure 1.2a &b). Hence, the study area was selected to be representative of the larger sub-Saharan Africa region in terms of geology, land use, demography, climatic and socio-economic conditions.

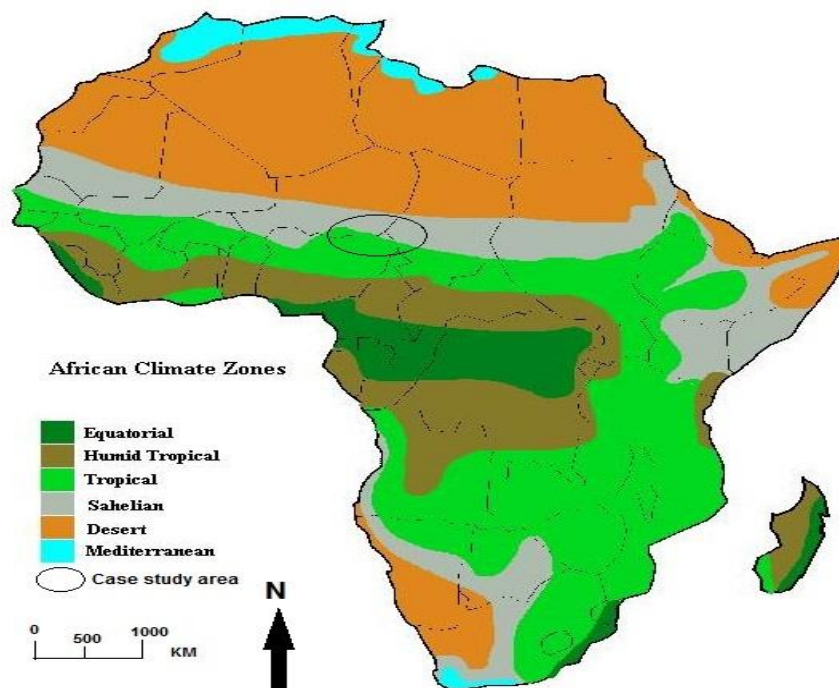
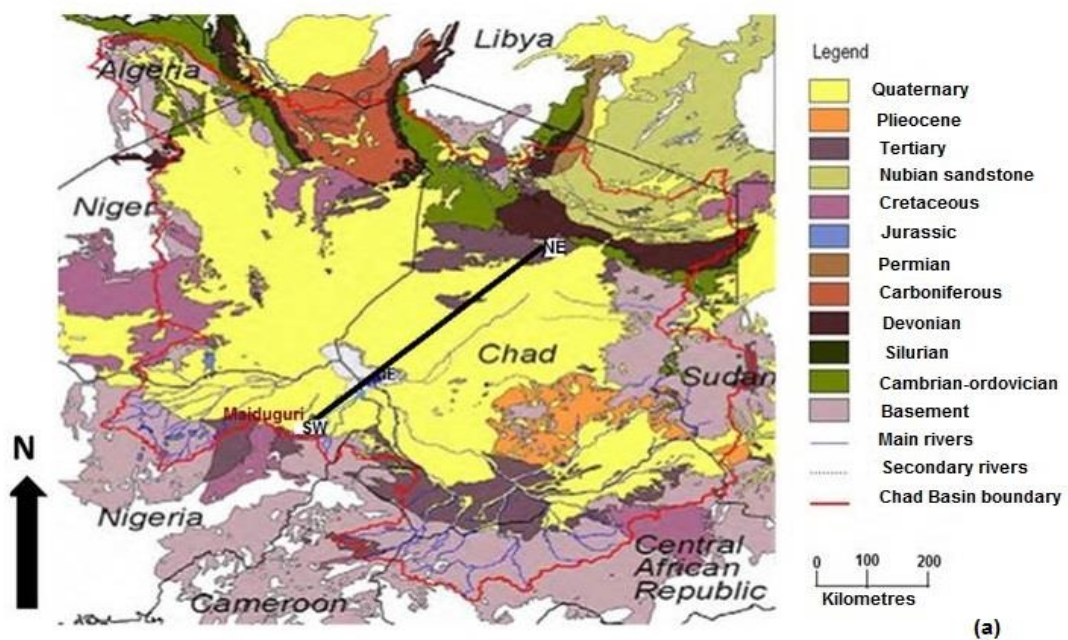


Figure 1.1 Map of Africa showing the study area and the major climatic belts (African Atlas, 2010)



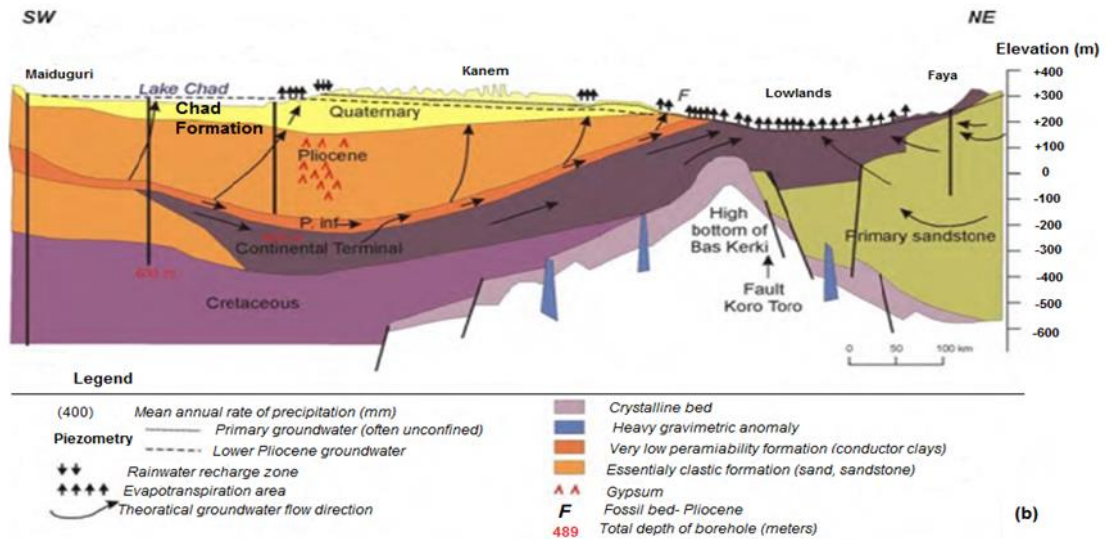


Figure 1.2a (upper) Regional Geology of the Chad Basin showing the SW-NE trend. Figure 1.2b (lower) cross section of (SW-NE) the multi-layered aquifer system of the Chad Basin. Modified from Schneider & Wolff (1992)

Socio-economically, Maiduguri metropolis is the largest city in the Nigerian sector of the Sudano-sahel region of West Africa. Thus, they were selected to represent a wide range of cases occurring in the region. Also, it is important to note that the Sudano-sahel region is an area with uniform climate and vegetation (Figure 1.1), similar hydrogeology, and comparable population distribution (Figure 1.3). Thus, Maiduguri metropolis is no exception and it will be a very vital representative case study for the whole region.

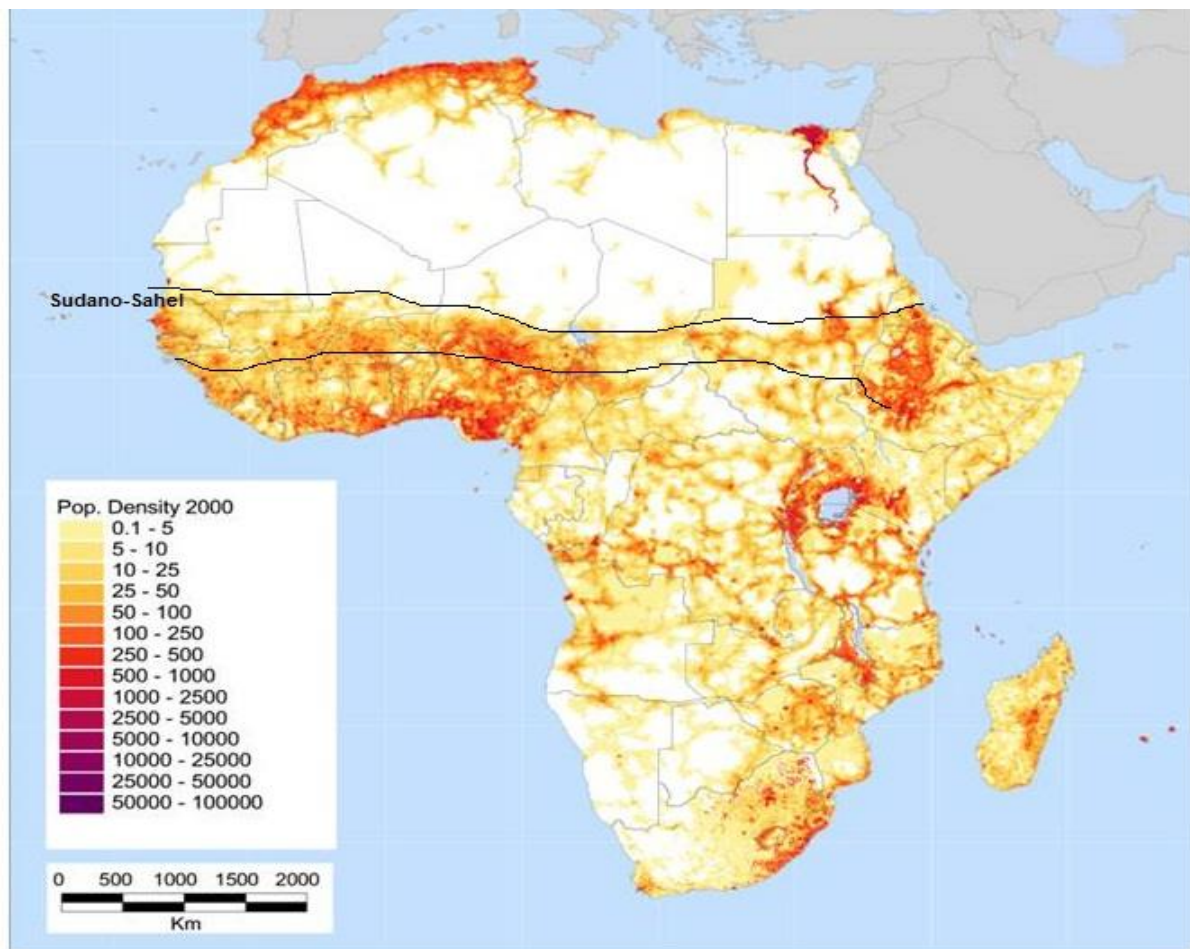


Figure 1.3 Map of Africa showing the Population distribution across the Sudano-sahel region. Modified from World Bank (2012)

The case study methodology adopted by this study is good for understanding contemporary societal problems that cannot be manipulated in real sense. Also, this case study will be a useful tool for investigating the preliminary causes of groundwater contamination which will serve as a basis for the development of a feasible and a realistic groundwater protection framework in sub-Saharan Africa region. Lastly, this case study will be useful in advancing the existing knowledge and will proffer solutions to the existing and presumed future problems of groundwater contamination in the region as no such study exists in the case study area.

The justification stated above will bridge the existing gaps by investigating the potential threats to water quality in the upper unconfined aquifer system of the Chad Basin around Maiduguri in north-eastern Nigeria. This aquifer is a major water supply source for the city; with more than 80% of the residents obtaining their domestic water supplies directly from it (Bunu, 1999). The aquifer is hydraulically connected to the Ngadda River, which drains the city (Isiorho and Matisoff, 1990) (Figure 1.4). This river–groundwater system is threatened by the impact point and non-point sources of contamination across the city (Bakari, 2014a).

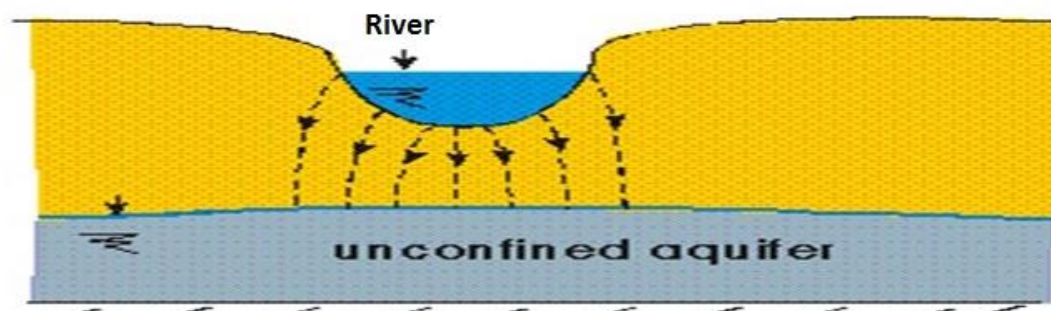


Figure 1.4 Conceptual representation showing River-aquifer connectivity. Modified from Isiorho and Matisoff (1990)

This negative impact is significant in many areas of Maiduguri metropolis where human, residential and commercial wastes are indiscriminately disposed of (Figure 1.5a and b). Also, the hydraulic connectivity, between the river and the upper aquifer, serves as a pathway of groundwater contamination due to inflow of poor quality river water into the aquifer. As a consequence, it poses unacceptable health risks to the local population; most especially on the urban poor who largely depend on the groundwater (Chilton, 1999; Wakida and Lerner, 2005; Putra 2008).

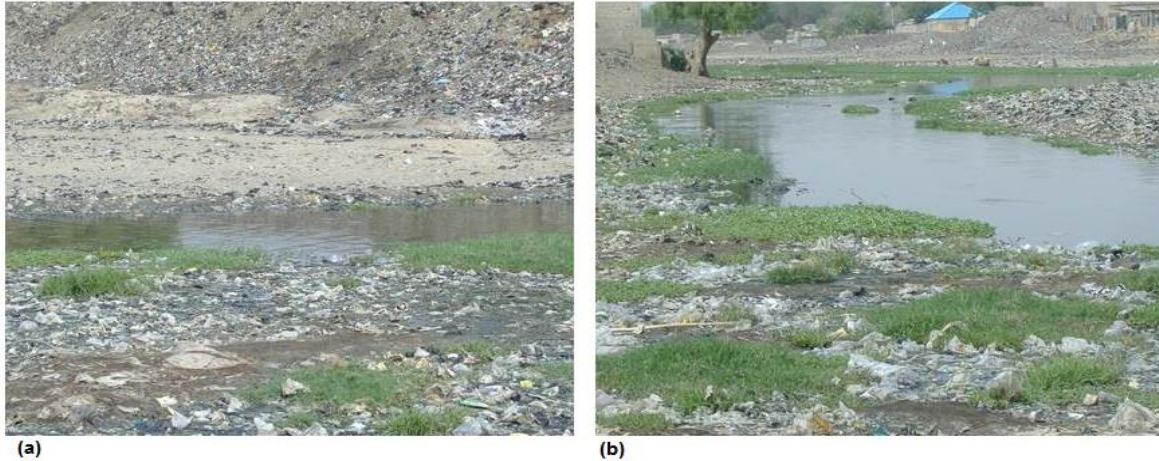


Figure 1.5 (a and b) Residential and commercial solid wastes disposed at the River Ngadda bank in Gwange area of Maiduguri metropolis

1.2 Justification for the study and rationale for a case study

In sub-Saharan Africa region, many countries including Nigeria failed to meet their Millennium Development Goal (MDG) targets on access to improved water and sanitation by the year 2015. Despite the intensive effort of the Federal Government on implementation of water and sanitation projects over the past two decades in Nigeria, the percentage of population with no satisfactory water and sanitation facilities is still high and on the rise especially in the urban areas.

According to a recent World Bank (2013) report, the impacts from poor sanitation and hygiene costs the economy of Nigeria to the tune of N 444 Billion (US\$ 2, 978, 000) annually, or the equivalent of 1.3% of its annual Gross Domestic Product (GDP). Also, the WHO (2012) estimates that diarrheal diseases caused by poor sanitation and water in Nigeria amounts to 124, 400 deaths of children under five years old annually.

In the study area, groundwater resources are facing significant pressure to provide for the socio-economic needs of the growing population. Also, the inadequate institutional framework, constraints in policy formulation and stakeholder exclusion in decision making in the management of water resources have been identified as the major limiting factors for the attainment of sustainable groundwater management in the study area and the entire region (Adelana, 2006). Also, the approaches to groundwater management in the case study area is inadequate, guidelines for mitigating the impacts of onsite sanitation systems on groundwater are non-existent. Furthermore, the study comes at a critical moment when many countries across Africa are transitioning from the Millennium Development Goals (MDGs) to the Sustainable Development Goals (SDGs); in ensuring sustainable livelihood of their citizenry.

Therefore, this study aims to address the abovementioned gaps by taking Maiduguri metropolis as a local case study area in sub-Saharan Africa. This is because guidelines for mitigating pollution sources impact on groundwater are absent in the current management and operational system. Thus, effective strategies that will ensure the achievement of the SDGs by 2030 are limited in the region. Strategies that mitigate the negative impact of urbanisation and population growth are lacking. These strategies if practically developed will be of paramount importance to the region. These include sustainable strategies such as; mapping anthropogenic pollution sources, identification and inclusion of key stakeholders in groundwater management, educating and enhancing the capacities of water user groups, periodic

assessment and monitoring of water quality and the provision of adequate legislation and enabling environment.

Additionally, the lack of relevant environmental, hydrogeological, and socio-demographic data poses more challenge to the development of sustainable groundwater management strategies in this region. In this respect, most hydrogeological research in sub-Saharan Africa are focused on addressing technical aspects of hydrogeology (Garduno et al., 2010; Foster et al., 2012; Taher et al. 2012) thereby giving less consideration to the social aspects. Consequently, the increasing uncertainties linked to urbanisation and population growth remains a critical issue on both local and global scale; therefore, it is necessary to adopt an integrated science of the people and water, which will explore the impacts and dynamics of human activities on the underlying groundwater systems.

Furthermore, the study was motivated by principle number 2 (Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels) of the Dublin Statement on Water and Sustainable Development 1992, and a more recent call in Hydrological Processes for a new science of water in the new Scientific Decade 2013-2022 of the International Association of Hydrological Science (IAHS) (Montanari et al., 2014). This is dedicated to further the investigations on change in water system and society; it treats humans and their activities as endogenous features of the water cycle. Through water consumption, pollution and policies, it can address many and varied

water-related challenges in the Anthropocene (Sivapalan et al. 2011; Montanari et al. 2013; and Gober et al., 2014; Sivapalan et al., 2014; Re, 2016).

The examination of this integrated science will be achieved in this study by bringing together the social and technical components of hydrogeology in addressing the persistent societal problem of groundwater contamination; attributed to the impact of above ground anthropogenic activities (Figure 1.6). As outlined (Figure 1.7), the integrated methodology developed by this study has two major environments of operation i.e. the above and the below ground environments respectively. The above ground component is social sciences dominant, it constitutes the identification and characterisation of pollution sources, engagement of relevant stakeholders for groundwater protection decision-making, and the development of sustainable framework; all take place at this level (above ground).

The social component allows the exploration of the sociological and socio-cultural perceptions of the stakeholders towards the potential anthropogenic contaminant sources. Additionally, the inclusion of stakeholders will enable the implementation of management actions needed to ensure sustainability of groundwater resources. Here, social tools or stakeholder participatory methods such as interviews, focus group discussions and household questionnaires are employed in evaluating the causes and remedies of groundwater contamination.

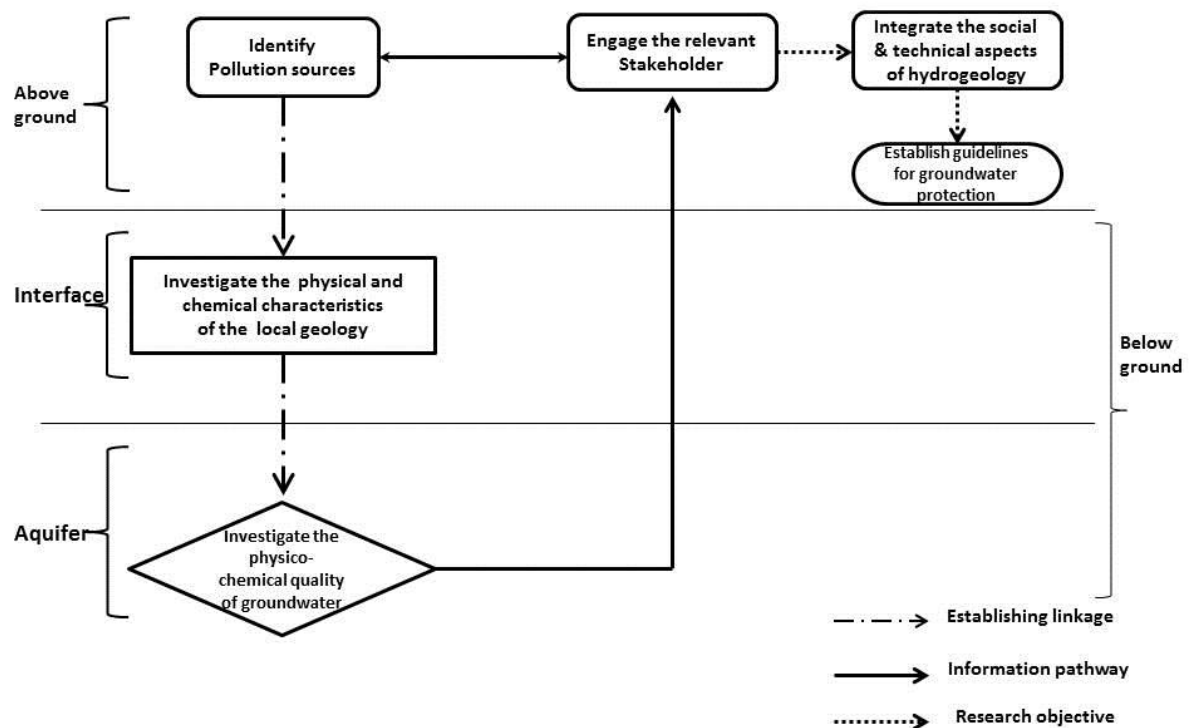


Figure 1.6 socio-hydrogeology outline

The below-ground component is purely technical (geological/ hydrogeological); it is sub-divided into the interface and the aquifer zone respectively. The interface will involve the investigation of the physical and mineralogical characteristics of the sediments/ or local geology in determining their distribution, sorting, and composition.

The aquifer section forms the groundwater body; here investigations of the Physico-chemical characteristics of the groundwater quality will be determined. In this respect, emphasis will be given to anthropogenic indicator contaminants because of their connection with the above ground anthropogenic activities. Here analytical

techniques of hydro-geochemical analyses will be employed in determining the extent of contamination across the study area. Also, a modelling of a selected anthropogenic indicator parameter will be carried out in determining the future trends of the contamination in the case study area. Particularly, chloride concentration will be modelled to determine impact of pit latrine on groundwater. This is because chloride is an excellent parameter that indicates faecal contamination.

The overall aim of the study will be achieved by tailoring the findings of both the technical and social aspects in establishing sustainable guidelines that can be practically applicable in the study area and other similar case studies across sub-Saharan Africa region. These guidelines will provide realistic and practical solutions to the existing problems in the case study area. The integrated and interdisciplinary approach envisioned by this study is becoming increasingly accepted as a way forward to addressing complex groundwater issues (Jakeman and Letcher, 2003; Giupponi et al. 2006; Re, 2015).

The integrated approach adopted by this study will provide opportunity for developing alternative guidelines for groundwater management, which cannot be achieved from mono-disciplinary stances alone. In this respect, Croke et al. (2014) have combined hydrological modelling with socio integrated assessment for water management in Australia. However, it is worthy to note that the integration of human and environmental issues remains a major problem in the policy world (Tress et al., 2003). This integrative view point was also expressed by many authors (Parker et

al., 2002; Winder, 2000 and Costanza, 2003; Winder 2003; and Jakeman and Letcher, 2003).

The schematic plan of this study (Figure 1.7) below shows the arrangement and connections of the various chapters as presented in this thesis.

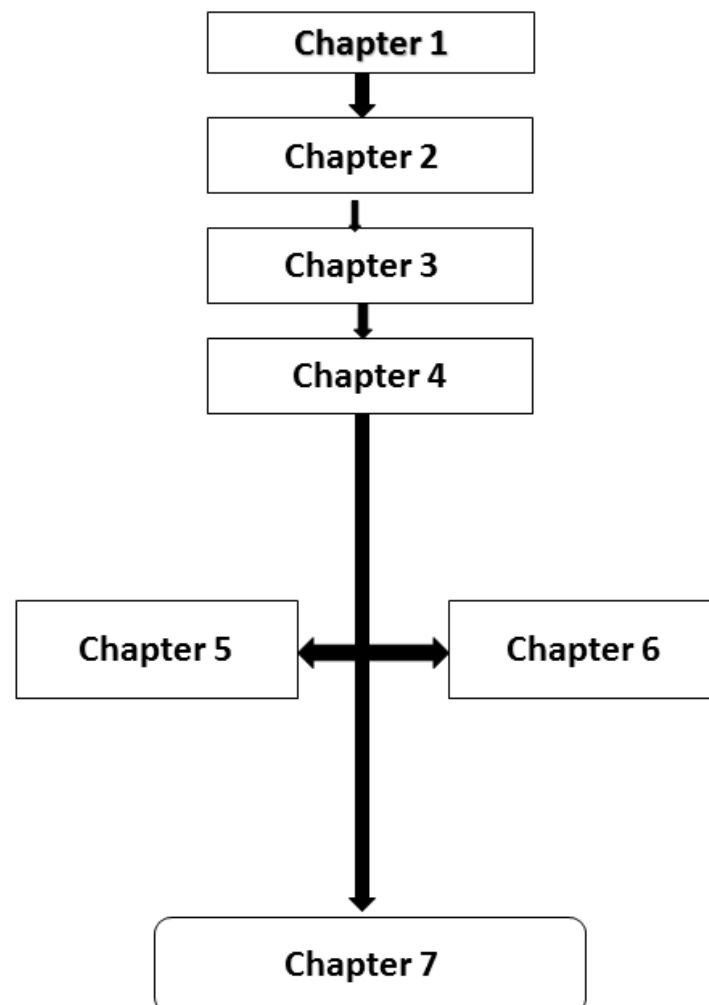


Figure 1.7 Research Outline

Additionally, it is worthy to note that the integration of the social and technical aspects of hydrogeology as proposed by this study might be subject of criticism in

the future. This is because the study is exploratory in the case study area and aims to contribute practically to the evolving subject of socio-hydrogeology.

The rationale for adopting the case study methodology is because it is more suitable and practical in addressing societal problems (Oats, 2006). Another advantage is that information obtained can be utilised to develop a theoretical proposition on the study area (Hartley, 2004). In addition, Yin (2009) has further stated that the benefit of a single case study is that the researcher has access to areas that were previously not investigated, and the resulting information is revelatory.

Thus, the single case study approach adopted by this study will investigate the coupled human-groundwater system including the physical and sociocultural mechanisms that affect groundwater quality from multiple perspectives. The findings of this study can be replicated in areas with similar characteristics across the sub-Saharan Africa region, and can be utilised to understand the relationship between above ground anthropogenic activities and below ground hydrogeological systems. This is because access to safe, clean and affordable drinking water and sanitation remains a mirage in many African countries.

The case study approach of this study endeavours to investigate the circumstances and dynamic conditions of an interrelated hydrogeological system. According to Stake (1988), the special aspect of the case study approach is that it focuses on one phenomenon so as to understand it in-depth in its natural condition. Furthermore, the

case study's unique strength is its ability to deal with a variety of evidence from multiple sources and questions about current set of events can be answered without any control of the researcher, making the finding authentic. The case study protocol increases the reliability of the case as it keeps the researcher focused on the subject of the case study (Yin, 2003).

1.3 Aim and objectives

The overall aim of the study is to develop methodologies that can mitigate the impact of above ground anthropogenic activities on groundwater resources in ensuring their sustainability in sub-Saharan Africa region. Taking Maiduguri metropolis (the chad basin) as a case study area, the following objectives have been formulated:

- To investigate and assess the multitude of above ground anthropogenic activities and their impact on groundwater quality in a typical sub-Saharan Africa urban centre.
- To critically evaluate the key factors that is responsible for both natural and anthropogenic contamination and suggests ways of protecting the underlying aquifers in the sub-region.
- To evaluate the problems of groundwater contamination in the case study area using a methodology for the engagement of the various stakeholders in addressing the situation; which can be replicated across the sub-region.

- To carry out modelling of anthropogenic indicator contaminant and establish sustainable framework for the protection of vulnerable aquifers in selected case study area.

1.4 Research questions

In addressing the myriads of existing gaps in the case study area, the study carried out an extensive literature review (Chapter 2) and topically scaled down the relevant issues identified therein; which the aim of the study intends to achieve. Thus, the research questions of the study were informed by both the literature review and the prevailing scenario of the case study area. They are intended to provide insights and address the research problems as well as the existing gaps. The following are the research questions:

- What is the current situation with regards to groundwater management in sub-Saharan Africa urban centre (Maiduguri metropolis)?
- What is (are) the potential source(s) of contamination that is (are) likely to affect the underlying groundwater resources in these countries?
- How can individuals/organisations responsible for and affected by contamination be involved in addressing the current and emerging problems?
- What is the current management framework and what can be done to develop a robust and a sustainable framework that will ensure the protection of groundwater from anthropogenic sources of pollution?

1.5 Methodology

As stated earlier (section 1.2), the study adopts a case study strategy that utilises a mixed (multiple) method research methodology that employs both quantitative and qualitative tools of data collection. The quantitative strand; includes field measurements, water level measurement and taking representative groundwater and sediment samples using onsite field instruments and techniques, as well as their subsequent laboratory analyses. Others are household survey data collection and analysis.

The above named methods were achieved by carrying out a detailed reconnaissance survey between 2012 and 2014. The first field work was carried out between March and May 2012; during this period, topographical and geological maps were used to determine the local geology and the various land use activities of the area. Pictures of the various sites were taken, and field observations were made.

Also, during the second round of field work in Maiduguri, the researcher in collaboration with a technologist from the University of Maiduguri and 2 independent research assistants (ad-hoc) carried out a comprehensive inventory of the potential pollution sources between January and February 2013. In this regard, the case study was divided into two major sites; in order to enable phased and detailed assessment of the aforesaid sources. In each case, detailed characteristics of the sites visited were recorded in the field log book. This allowed the conceptualisation of the system

and practical linkages between the pollution sources and environmental degradation were established. Lastly, sampling points for the collection of representative groundwater and sediment samples were identified. A comprehensive detail of the methodological approach of the study is outlined in chapter 4.

The qualitative strand includes an extensive desktop literature review carried out in the early stage of the study from October 2011 to February 2012. This was aimed at critically evaluating the existing situation and approaches to groundwater management in the case study area and across sub-Saharan Africa. Step by step details of the qualitative methodological approach is outlined in chapter 4.

1.6 Structure of the thesis

This thesis is presented in 10 distinct but interrelated chapters that are summarised as follows:

Chapter 1 presents a background of the study and the case study area. It outlines the problem statement, research justification, rationale for a case study, and aim & objectives of the study.

Chapter 2 presents the literature review; the concepts of the origin and occurrence of groundwater including the hydrological cycle, the evaluation of the types of geological formations, assessment of the various groundwater pollution sources; natural and anthropogenic and their potentials. The chapter also, assesses the aspects of groundwater contamination and the need for effective management and

utilisation in Africa and sub-Saharan Africa. Lastly, various groundwater management approaches and their challenges (institutional and socio-economic) to effective management across sub-Saharan Africa region were synthesised.

Chapter 3 presents a detailed description of the case study area; location, demography, climate and vegetation, relief, geology and hydrogeology, and the current problems affecting the case study area.

Chapter 4 presents the design and methodology adopted for the study. It describes the various fieldwork and the analytical techniques employed in the study.

Chapter 5 presents the results and discussions of the social and hydrogeological dimensions of the study. Result from stakeholder engagement (the interviews, focus group discussions and household surveys) and hydrogeological investigations were presented and discussed in this chapter.

Chapter 6 aspects of chloride modelling and the development of the alternative guidelines for protecting groundwater in the case study area are presented in this chapter.

Chapter 7 presents the summary and conclusion, and recommendations for further research.

1.7 Scope and limitations of the study

This study was undertaken with the following scope and limitations:

1. While the outcomes of the research can be applicable to other areas especially in sub-Saharan Africa countries, the discussions presented are based mainly on the findings investigated in a local case study (Maiduguri metropolis). Though, the findings can be transferable across the region especially the Sudano-sahel region, it is worthy to mention that the northern fringe of the region is surrounded by basement complex environment which limits the assumptions on the type and nature of processes occurring within the sedimentary environment. Taking this into consideration, practical limitations exist in the application of the guidelines developed by this study in the entirety of the sub-region thereby affecting the overall aim of the study.

2. Although the significance of microbial contaminants to the assessments of groundwater quality is greatly appreciated, this study's laboratory analytical assessments of groundwater quality were limited to the physico-chemical parameters. In this respect, the microbial parameters were not included in the first design framework of the study. Subsequently, constraints of resources (funds) at the stage of data collection compelled the researcher to exclude these parameters; this will greatly limit the consideration of this study as a general standard for comparison by other studies across the sub-region.

3. Chemical analyses conducted were only a snapshot of the local situation; therefore, they are not sufficient to provide details of the regional-temporal and spatial compositional variations of groundwater quality. Taking this into consideration, it is vital to carry out regional assessment of groundwater quality trends across the sub-region and compare it with the findings of this study.

4. The study is limited to models developed based on geological, hydrogeological (primary and secondary) data obtained. It is noteworthy that the modelling herein is theoretical, therefore major limitation exists and future studies need to test the validity of this model.

1.8 Summary and conclusion

The importance of groundwater for sustainable development in sub-Saharan Africa cannot be over emphasised. This chapter has made it clear that socio-hydrogeology can be very useful tool for achieving sustainable groundwater management. Incorporating social dimensions into hydrogeological problems in developing sustainable guidelines for mitigating the impact of onsite sanitation system; especially pit latrine in the study area. This chapter presented the background to the current problems affecting groundwater resources in the study area, and suggests strategies for addressing the challenges. The chapter outlined the aim and objectives of the study, methodologies, and the justification of the study. Others are the scope and limitations of the study and research outline. The next chapter presents the literature review component of the study.

CHAPTER 2

ASPECTS OF GROUNDWATER CONTAMINATION, MANAGEMENT, & UTILISATION IN SUB-SAHARAN AFRICA

2. Introduction

The objective of this chapter is to review the key aspects of groundwater occurrence and contamination processes in sub-Saharan Africa region. The chapter outlines the review of the aspects related to groundwater including their significance, as well as the types and nature of the physical, chemical, and biological processes and transformations occurring in the natural sedimentary environment. The chapter continues with the outlining of the organic and inorganic contaminants found in a typical hydrogeological environment. It also includes an assessment of the various groundwater pollution sources; natural and anthropogenic and their potentials. Also, the chapter presents a review of the groundwater quality standards and the adopted groundwater sampling method in the study.

Besides, the chapter presents a synthesis on the issues related to occurrence and aspect of contaminant processes in a typical sedimentary basin in sub-Saharan Africa. Additionally, overview of the existing approaches to groundwater management in sub-Saharan Africa, institutional frameworks and instruments available for groundwater management are presented. Lastly, the chapter evaluates the various sustainability based approaches used in the management of groundwater resources.

2.1 Groundwater

As the name implies, groundwater is the water that is found in the earth's sub-surface (Figure 2.1); contained between the pore spaces of sediments and fractures of crystalline rocks (Freeze and Cherry, 1979; Younger, 2007; Mendes and Ribieiro, 2014). It primarily originates from precipitation (rainfall and snow); after rain or snow fall, a significant volume of water infiltrates into the ground (Figure 2.2) and continues to exist in the zone of aeration or saturation accordingly, this precious and vital natural resource is central to human life and economic prosperity. Previous studies (Lvovitch, 1972; Buchanan, 1983; Foster et al., 1998; Chilton, 1992; 1996; NGWA, 2010) show that groundwater is an important component that contributes significantly to the global hydrological system and makes up about two-third of the accessible global fresh water reserves.

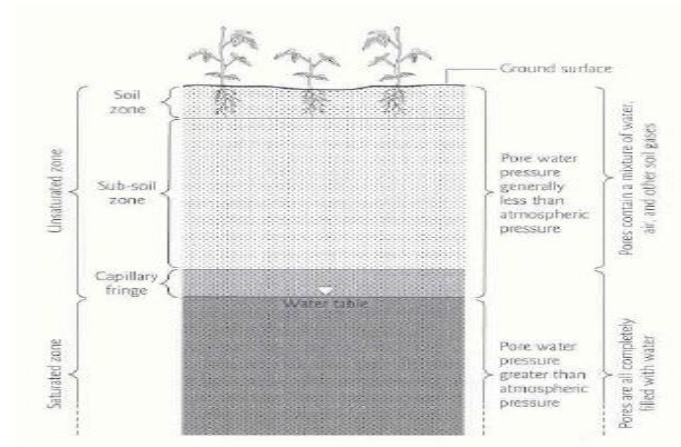


Figure 2.1 A cross-section showing the distribution of groundwater (USGS, 2010)

Currently, it is believed that about 85% of the total population of sub-Saharan Africa depend directly on this vital resource (UNDP, 2000). Studies carried out in Africa (Todd, 1980, Chapman, 1996, USEPA, 2001; McDonald et al., 2005; NGWA, 2010); USGS, 2010; UNDP, 2010) showed that groundwater accounts for about 80-90

percent of agricultural water utilisation and domestic water supplies in the rural areas of Africa.

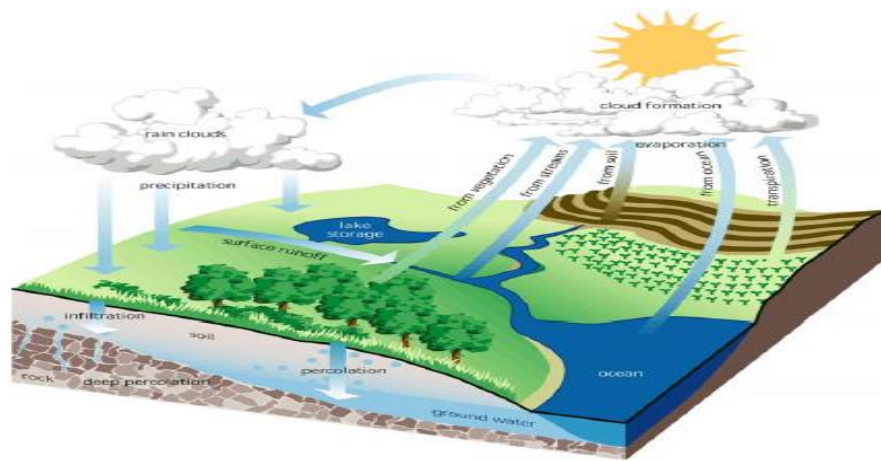


Figure 2.2 Hydrological cycle describing origin of groundwater (Chilton, 2002)

In sub-Saharan Africa, groundwater occurs in four major hydrogeological environments. Each of these environments needs the application of different hydrogeological methods for exploring and abstracting groundwater resources (Lake and Soure, 1997). Furthermore the different hydrogeological environments also require different strategies in ensuring the protection of their underlying aquifers.

At present, over 90% of the African population depend directly on groundwater (UNDP, 2000). In this regard, MacDonald and Davies (2000) carried out a holistic review of the occurrence of groundwater in sub-Saharan Africa and identified the four distinct environments as crystalline basement, volcanic rocks, consolidated sediments, and unconsolidated sediments. Also, according to a British Geological Survey report (2000) about 220 million people in sub-Saharan Africa region get their

groundwater supplies from crystalline basement rocks. Consolidated sedimentary rocks sustain about 110 million across the sub-region while unconsolidated sediments sustain about 60 million people. Lastly, a total of about 45 million people get their groundwater supplies from volcanic rock environments (BGS, 2000).

2.2 Characteristics of hydrogeological environment in sub-Saharan Africa

According to their origins, mode of formation, and occurrence; hydrogeological environments and aquifer materials in sub-Saharan Africa can be classified as deposits of various sedimentary or metamorphic rocks. Aquifers that trace their origin from fluvial processes are typically made up of gravel, silt, and clay which are subsequently subjected to diagenesis, cementation, and other secondary sedimentary processes (Freeze and Cherry, 1979; Yaron et al., 2012).

Aeolian deposits containing sand or silt are more homogeneous than fluvial deposits. Globally, glacial, fluvial, and Aeolian-deposits; including glacial till, glacio-fluvial, and glacio-lacustrine sediment are the chief aquifer materials. Sedimentary rocks, containing sandstones and carbonates constitute the materials or bodies of major hydrogeological importance (Smith et al., 2011).

According to Grey et al. (1995) sandstone alone, makes up about 25% of the entire sedimentary rocks; they are mostly formed from the transportation, layering, and compaction of unconsolidated materials, which are consequently cemented by materials like quartz, calcite, and clays in the environment of their deposition. On the other hand, carbonate rocks are chiefly made up of aragonite often occurring as calcite and dolomite with small proportions of clay. These geological materials have porosity that ranges between 20 to 50%, but in contrast to the sandstones, their porosities tend to decrease with increasing depth (USGS, 2010). Crystalline materials such as Igneous and metamorphic rocks have very low porosities often smaller than 2%; they are characterised by a minute permeability (Yaron et al., 2012). A summary of the various hydrogeological environments and their mineral constituents are summarised in Table 2.1.

Table 2.1 Summary of the major hydrogeological environments and their composition in sub-Saharan Africa

Hydrogeological environment	Mineral assemblage
Sandstone	Quartz, Feldspars and other rock forming minerals
Siltstone	Quartz and clay minerals
Clay	Clay minerals
Limestone/dolomite	Calcite, aragonite, and some rock forming minerals
Basalt	Plagioclase, Augite, Olivine, Pyroxene and some rock forming minerals
Granite	Feldspar, Plagioclase, and Quartz

Source: Yaron et al. (2012)

2.2.1. Hydrogeological environment solid phase

The solid phase of the hydrogeological environment is a permeable media made up of an agglomeration of both inorganic and organic natural materials in different segments of development. The surface area and the chemical properties of the solid phase are the foremost factors that control the behaviour of chemicals in the subsurface environment (Molle, 2009). Based on their origin, minerals that constitute the solid phase are clustered into two broad classes (Table 2.2). Primary minerals are those that have not undergone chemical modification since the time of their crystallisation from the molten magma and their subsequent deposition. Primary minerals have a tendency to have low surface area (e.g., silica minerals) and low reactivity, these characteristics essentially affects the physical transport of water, dissolved chemicals, colloids, immiscible (in water) liquids, and vapours (Newson, 2009).

On the other hand, secondary minerals are those minerals that results from the weathering and decomposition of primary minerals and they later precipitate into new, chemically separate minerals. Secondary minerals ordinarily tends to have high to very-high surface area (e.g., clay minerals), and high reactivity that has the potentials to affect the transport of chemicals, and they have the tendency to retain and release against and from the solid phase (Goldsten et al., 2012). Also, the solid phase can ultimately prompt the degradation of chemical compounds, through its effects on the water-air ratio in the sub-surface and on microbiological processes (Berkowitz et al., 2008).

Table 2.2 Summary of primary and secondary minerals

Primary minerals	Secondary minerals
Quartz (SiO_2)	Kaolinite
Feldspars $(\text{Na,K})\text{AlSi}_3\text{O}_8$	Smectite
Muscovite $\text{KAl}_2(\text{Al Si}_3\text{O}_{10})(\text{OH})_2$	Vermiculite
Hornblende $(\text{Ca, Mg, Fe, Na, Al})_7 (\text{Al,Si})_8 \text{O}_{22} (\text{OH})_2$	Chlorite
Augite $(\text{Ca, Mg, Fe, Al}) (\text{Si, Al}) (\text{Si, Al})_2 \text{O}_6$	Imogolite
Olivine $(\text{Mg, Fe})_2 \text{SiO}_4$	Gibbsite
	Goethite
	Hematite
	Birnessite
	Calcite
	Gypsum

Source: Berkowitz et al. (2008)

2.2.2 Hydrogeological environment Liquid Phase

Within the underlying hydrogeological environment, there are two clearly defined liquid phase regions (Figure 2.3). The first zone encloses water near the solid surfaces and is seen as the most essential shallow reaction zone. This zone is affected by the physical properties of the solid phase and it controls the diffusion of the mobile segment of the solute adsorbed on the solid phase. The second zone encompasses the free water zone, which has the affinity to control the liquid and chemical flow in the medium (Peach et al., 2000; Berkowitz et al., 2008).

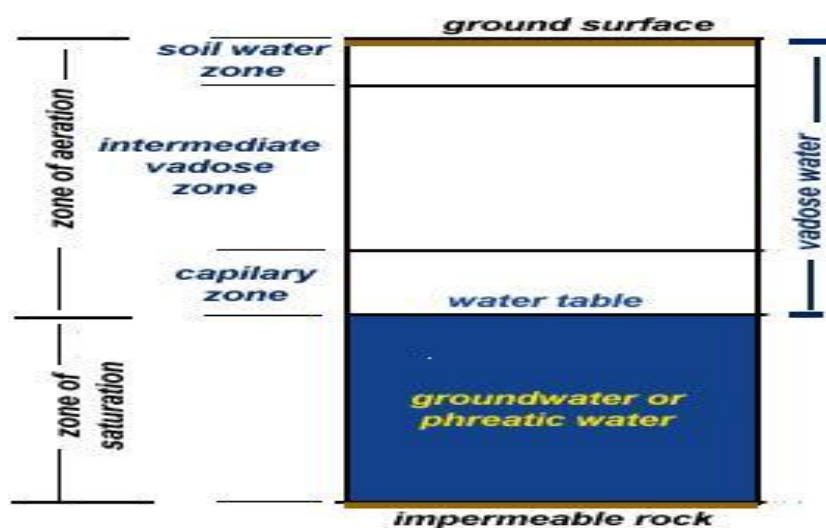


Figure 2.3 Configuration of sub-surface liquid phase environment (USGS, 2010)

The configuration and reactivity of the liquid phase is a function of the infiltrating water quality and is often controlled by the various materials that make up the region, and the dynamics resulting from the solid phase, bacteriological processes, and the gas phase. The subsurface liquid phase is largely an enormous and unhindered system, its composition derived from the dynamic transformation of dissolved elements occurring in countless chemical species over a variety of reaction time scales (Weinhold, 1996; Berkowitz et al., 2008; Yaron et al., 2012).

2.2.3 Hydrogeological environment Gaseous Phase

The subsurface gas phase is composed mostly of the most common gases; CO₂, N₂, and O₂, which are the most important gases occurring in the atmospheric cycle. This gaseous phase is controlled by the moderate porosities and moisture contents of the subsurface environment, and can support the movement of organic fragments in the

vapour phase; it can also affect microbiological processes and subsequently define chemical persistence in near surface environment (Yaron, 1996; White and Howe, 2003).

Gaseous passage through pore spaces makes the subsurface gaseous phase an essential conduit for subsurface pollution by unpredictable toxic chemicals. From the gaseous phase, chemicals might be adsorbed on to solid surfaces or can be dissolved in subsurface water. Also, the transport of water as vapour into pores might lead to the formation of a water layer that covers potential vacant sites for nonpolar gaseous pollutants, thus reducing pollutant fixation on the solid phase (Paul and Clark, 1989; Waylen et al., 2011).

2.3 Types of Contamination processes occurring in the Sedimentary Environment

Physical contamination processes occurring in the natural sedimentary (hydrogeological) environment are governed by four principal mechanisms: advection, dispersion, straining, and physicochemical particle-surface interactions (McDowell-Boyer et al. 1986; Zheng and Bennett, 1995; Berkowitz et al., 2008). Sorption of contaminants onto the surfaces of geological materials (sediments) in the saturated zone is an essential physical process that decreases the concentration of organic and inorganic contaminants in the groundwater (Lapworth et al., 2012).

Numerous studies have investigated the sorption potentials of geological materials (e.g. Casey et al., 2004; Wang et al., 2009; Olshansky et al., 2011), most of the studies revealed that soil carbon and clay materials play significant roles in the physical processes occurring within the sedimentary environment. Many scholars (e.g. Redshaw, 1979; Fetter et al., 2004; Van Genutcten et al., 2005; Mondal and Singh, 2009) concede that the physical processes are controlled by Darcy's Law (see section 2.8.1.7 for more details on Darcy's law) in the unsaturated zone of the hydrogeological environment.

Chemically, adsorption is the chief chemical contamination processes occurring in the natural hydrogeological environment (Price et al., 2000; BGS, 2003). Accordingly, adsorption eliminates toxic compounds within the subsurface, and it affects the fate of contaminants within the sedimentary environment (Haria et al., 2003; Yaron et al., 2012). In this regard, many authors (Oades and Muneer, 1989; McBride, 1994; Petersen et al., 1995; Greenland and Hayes, 2001; Sparks 2006; Hasset and Banwart, 2009) have reviewed and documented all the issues related to adsorption of ionic and non-ionic compounds in different hydrogeological environments.

Furthermore, a set of biological and biogeochemical processes are occurring in the geo-system. The presence of active microscopic organism populations is mainly responsible for the biogeochemical transformation of contaminants (Alexander, 2000). Accordingly, the transformation process occurring in the hydrogeological environment could result due to primary metabolic reactions within the subsurface

(Keeney, 1983; 2002). Detailed list of the key biological transformation processes occurring in sedimentary environments are investigated and summarised by many authors (e.g. Lovely, 1993; Bollag and Liu, 1999; Paul and Clark, 2002; Sims and Pierzjinski, 2005; and Berkowitz et al., 2008).

Additionally, multitudes of ion exchange processes occur within this environment; where alkali metals derived from the primary minerals react with the various anions. Heavy metal cations derived from anthropogenic sources take part in exchange reactions with clay minerals, and cationic organic contaminants compete with mineral ions (Mc Bride, 1994; Hayes, 2001; Fetter et al., 2004; Yaron et al., 2012).

Lastly, several authors (Morgan et al., 1993; Rabus and Widdel, 1996; Bregnard et al., 1997; McRae et al., 1998; Broholm and Arvin, 2000; McQuarrie et al., 2001; Pabich et al., 2001; and Hartog et al., 2004) carried out geochemical investigation of potential anthropogenic contaminants such as nitrate, sulphate, and phosphate in a clastic sediment dominated hydrogeological environment. They all confirmed that the physical characteristics of sandstone formations tend to affect the geochemistry of these contaminants.

In another perspective, Cervantes et al. (2001), Smith (2002) and Olshanky et al. (2011) carried out an investigation and confirmed that complex organic compounds and petroleum products undergo biologically mediated biodegradation under aerobic and anaerobic conditions. Also, Reineke (2001) showed that bacteria found in the

subsurface initiate the oxidation of unsubstituted aromatic compound to form cis-dihydrodiol and by additional oxidation to form catechol. Furthermore, Smith (2001), Seiler and Vomberg (2005), Langman et al. (2008), and Cervantes et al. (2001) verified the prospect of microbially influenced degradation of complex organic compounds and petroleum products in a typical arid sedimentary environment.

Likewise, Cannavo et al. (2004) established a comparable pattern of denitrification potential in an unsaturated zone, beneath a corn field in a sedimentary environment. They argue that the rate of denitrification was controlled by the supply of organic carbon in the upper layers (<5m). At deeper depths exposure to nitrates becomes limited. Similarly, Rodvang and Simpkins (2001) investigated the reduction of phosphorus by biological processes occurring within the subsurface. They suggest that phosphorus can be adsorbed strongly to the particles of the clastic materials and is capable of combining with various metal cations such as iron, aluminium, manganese, and calcium to form stable and new minerals.

Lastly, the decrease in contaminant load in aqueous solution via sorption is doubtful considering the mobile nature of the anthropogenic contaminants; therefore the contaminant load is likely reduced by dilution through mixing with uncontaminated water or by microbial degradation of the contaminants prompted by reduction of nitrate under hypoxic or anoxic conditions (Finegan, 1996; Vomberg, 2005; Langman et al., 2008).

2.4 Groundwater quality standards in sub-Saharan Africa region

Generally, anthropogenic activities attributed to groundwater quality degradation have enticed many researchers (such as Foster et al., 2002; Morris et al., 2003) and international development partners working in Africa such as WHO, UNICEF, and World Bank and African Development Bank to call for the strict adherence to groundwater quality standards across the sub-continent and Africa as a whole.

Groundwater quality standards outline the allowable levels of contaminants found in groundwater. Quality standards are designed principally to protect the health of the citizenry, environment, and aquatic fauna and flora (USEPA, 2010). They are also regarded as regulatory mechanisms that list and specify the standard qualities of groundwater for the preferred domestic and industrial use (Morris et al., 2003).

As a global practice, most countries have their standard water quality criteria and guidelines that enable them to regulate the amount of contaminants allowed in their various water sources (Onemano and Otun, 2003). However, countries with minimal technological and economic capacities continue to struggle in developing their guidelines. In bridging this gap, the WHO rolled out its first set of global water quality standard in (1983-1984) and second (1993-1997), the WHO published the first and second editions of the Guidelines for Drinking-Water Quality (GDWQ), covering respectively the physical, chemical and microbiological aspects of water quality (WHO, 2006).

These guidelines are updated frequently based on the outcome of the global scientific research and consultations with various stakeholders in the water, health, and sanitation sectors (WHO/UNICEF, 2000). A universal and comprehensive information on the Guidelines for Drinking-water Quality which includes minimum procedures and specific guideline values, and how those requirements are intended to be used was documented and published by WHO (2011).

In sub-Saharan Africa, studies such as Foster et al., (2000), Morris et al. (2003) have shown that there is the need for developing countries to fully adopt and implement the anti-degradation strategies that will help mitigate the negative impacts of contaminants on underlying groundwater bodies (WHO, 2006; 2011). Furthermore, Henley (2000) and USAID (2009) stressed that most countries in sub-Saharan Africa are recently making attempts to implement the global standard of reducing the effect of harmful substances that affects their underlying aquifers.

Therefore, the proper implementation of the WHO guidelines in sub-Saharan Africa countries will ensure the safety of drinking water supplies will be achieved through the reduction of the concentration of contaminants to the barest minimum.

2.5 Groundwater sampling strategies and protocols

The general procedures for the collection of representative groundwater sample have been widely recognised in the literature (e.g. Barcelona, 1994; USGS, 2010; Guerin et al., 2014). Also, methodologies for the identification and monitoring of sampling points have been published in the last few decades (Kearl et al., 1994; USEPA, 2002; 2013; Barcelona et al., 2004; USGS, 2010; Greacen and Slivia 2012).

In general, the documented guidelines often consider groundwater sampling in the framework of overall monitoring plans, thereby providing simple details on how to obtain and handle the samples onsite and in the laboratory (USGS, 2010). However, the collection of a specified number of representative samples for hydrochemical and geochemical analyses varies according to the nature of study and the problems at stake (Claasen, 2006).

Therefore, there is no fix rule in selecting or choosing the type of parameters and number of groundwater samples to be analysed for investigative purposes (Wood, 2013). In view of this, Barcelona (2004) argues that the selection of the physical, chemical, and organic parameters is important in determining the quality of groundwater in assessing its suitability of groundwater for domestic consumption. Also, Tricks (2009) stated that for investigative efforts, additional information can be included subsequently as the conditions of the case study become clear.

In the case of parameter selection, many authors (Hem, 1985; Cook et al., 1989; Parker and Clark, 2002; Guerin et al., 2014) conclude that the selection of

parameters for hydrochemical analyses can be determined by the researcher. Taking this into consideration, the study selected anthropogenic indicator parameters (anions) such as: Cl , SO_4 , NO_3 , HCO_3 , and PO_4 , others are cations such as Ca , Mg , Na , Cl , and Mg . These cations and anions can reveal the prevalent anthropogenic activity that results in the contamination of groundwater (Kerndorff et al., 1992; Tricks, 2009; USGS, 2010; Tran et al., 2014).

2.6 Groundwater Management and Utilisation in Africa

Groundwater management in sub-Saharan Africa is characteristically more complicated because of three defining features (Tuinhof et al., 2011). Firstly, unlike surface water, groundwater is easily appropriated, this allow individuals to possess rights to the water under their domain (Weinjen et al., 2012). Secondly, the readily available nature of groundwater enables the local water users from restraining governance within a catchment (Shiklomanov, 1999). Thirdly, it is often very difficult for even groundwater specialists to measure this invisible natural resource; thus, it is always difficult to manage what you cannot see (UNDP, UNEP and World Bank, 2000).

Even though natural factors have placed greater protection on groundwater against pollution in most parts of sub-Saharan Africa, up till today there are severe water quality problems in Africa especially around the large urban areas of the continent (UNDP, 2000; 2010). Most recently, a shift towards Integrated Water Resource Management (IWRM) as a policy initiative was adopted by most sub-Saharan African

countries (Biswas, 2004). The IWRM takes into cognisance the various individual groups, national governments, and multi-lateral regional organisations.

In sub-Saharan Africa, national and state or provincial water agencies are solely responsible for the management of groundwater resources (Pavelic et al., 2013). In most cases, groundwater is strictly governed by the various government agencies at the central and state or provincial levels across the region (Adelana, 2003). Also, according to the assessment carried out by AICD (2011), the institutional and regulatory framework for the management of this important natural resource is weak across the region. Also, Foster and Ait-Kadi (2012) revealed that sustainable groundwater management in sub-Saharan Africa failed due to weak governance structure operated by the responsible agencies. Sub-section 2.6.1 to 2.6.3 evaluates the approaches to groundwater management in the various sub-regions of sub-Saharan Africa.

2.6.1 Groundwater Management and Utilisation in the West African Sub-region

In West Africa, abundant sedimentary basins (the Iullemeden, Taoudeni, Chad, and the Senegal-Mauritania and the coastal basins of Gulf of Guinea) dominate the entire region; where thick sediments extend from the Quaternary to Cambrian. In this region, the bulk of the groundwater resource is used for drinking as potable water. According to a study carried out by some authors (Van Lanen, 1999; Adelana, 2003; Barry and Obuobie, 2011; Pavelic et al., 2013) groundwater accounts for about 93

percent in Niger, 75 percent in Nigeria, and 57 percent in Mali and Burkina Faso respectively.

2.6.2 Groundwater Management and Utilisation in the Southern Africa Region

In the Southern Africa region, groundwater is often regarded as the solitary source of water and is used for domestic, agricultural and industrial uses. In South Africa, Zimbabwe, Mauritius and Namibia there is a significant amount of groundwater used for irrigation (Braune et al., 2008; Tindimugaya, 2010; Nonde, 2011), in Tanzania, Kenya and Botswana they use it mainly for drinking and other domestic purposes (Ministry of Water Zimbabwe, 1987; Ndiritu, 2011; Pavelic et al., 2013). In this region, the urban water supplies (excluding small towns and villages) are supplied from surface water sources (UNDP, 2010). Groundwater management in African countries is the responsibility of the various government agencies as summarised in Table 2.3.

2.6.3 Groundwater Management and Utilisation in Eastern Africa Region

In Eastern Africa, the management of the available water resources are vested on the various national governments (Table 2.3) ((World Bank, 2010). Drinking water supplies are obtained from groundwater in most rural areas and small towns. Statistics show that the dependence on groundwater in Ethiopia is 86% (Ayenew et al., 2005), Kenya (51%), Somalia (71%), Tanzania (58%), and 71% in Uganda (Tindimugaya, 2010; Tewari, 2009; Mumma et al., 2011).

Table 2.3 Summary of regional groundwater management institutions and legislation in sub-Saharan Africa region

Region/Country	Institution responsible for water management	Legal instrument	Source
<u>West Africa Region</u>			
Burkina Faso	Ministry of Environment and Water	Water Management Policy Act (2001)	Obuobie and Barry (2004)
Mali	Ministry of Mines, Energy and Water	Water Code (No. 02-006:2002)	Barry and Obuobie (2011)
Niger	Ministries of Hydraulics, Agriculture	Law No. 98-041	Barry and Obuobie (2011)
Nigeria	Federal Ministry of Water Resources, River Basin Development Authorities	RBDA Act 1986, WRA 1993, National Water Policy (2000)	Adelana (2003)
<u>East Africa Region</u>			
Ethiopia	Ministry of Water Resources	Proclamation No. 197/2000	Ayenew et al. (2005)
Kenya	Water Resources and Planning Department	Water Act Cap 372, Water Act 2002	Pavelic et al. (2012)
Somalia	Water Development Agency	Draft Water Act 2004	Ndiritu (2011)
Tanzania	Ministry of Water	Water Resources Act 2009, National Water Policy 2002	Kashaigili (2003)
Uganda	Ministry of Water and Environment	Water Act (2000), National Water Policy (1999), Water Resources Regulation (1998)	Tindimugaya (2010)
<u>Southern Africa region</u>			
Malawi	Ministry of Irrigation and Water Development	Water Resources Act 1969, Irrigation Act 2001	Pavelic et al. (2012)
Mozambique	Regional Water Administration Department	National Water Policy 1995, 2005	Pavelic et al. (2012)

South Africa	Department of Water Affairs and Forestry	Water Act 1956, Water Act 2005	Tewari (2009)
Zambia	Department of Water Affairs	Water Policy Document 1994, Cap 312 Laws of Zambia	Nonde (2011)
Zimbabwe	Zimbabwe National Water Authority	National Water Act, 2000	Masiyandima (2002)

2.7 Groundwater contaminants and contamination issues in sub-Saharan Africa

In many parts of Africa, groundwater contamination is largely attributed to human activities (urbanisation and agricultural practices) (Foster et al., 1998). Available groundwater resources in most parts of Africa are at risk of contamination due to the ever increasing impact of uncontrolled above ground anthropogenic activities (USEPA, 2011).

In this region, the major sources of groundwater contamination include on-site sanitation facilities, agricultural activities and other non-point sources (Foster et al., 1993; 1998; WHO/UNICEF, 2000; Putra, 2008). In conformity with this, Wakida and Lerner (2005) carried out an investigation across sub-Saharan Africa urban centres and confirm that these centres are the areas with the most significant pressure on groundwater systems.

Both anthropogenic and natural sources of contamination (Table 2.4) are playing a significant role in the deterioration of groundwater quality. To this effect, the potential contaminant types and their sources as well as the potential health issues related to them in the case study area are summarised in Table 2.4.

Table 2.4 Summary of groundwater contamination problems

Problem	Causes	Concerns
Anthropogenic pollution	Poor aquifer protection against human discharges and leachates from anthropogenic sources Increasing agricultural activities	Pathogens, nitrates, ammonium salt, Chloride, sulphates, heavy metals, complex organic compounds Nitrates, chlorine, pesticides
Naturally occurring contamination	Associated with dissolution of minerals in the sub-surface	Mainly iron, fluoride, arsenic, iodine, manganese, aluminium, magnesium

Source: Foster et al., 1998

The likely sources of pollution and their potential health effects are summarised in Table 2.5 as follows:

Table 2.5 Potential contaminants and their associated health issues

Nature of contamination source	Type of contaminants	Potential health effects
<u>Anthropogenic</u>		
Urbanisation and population growth	Chloride	Excessive amounts leads to congestive heart failure
	Nitrate	Methaemoglobinaemia
	Sulphate	Catharsis in adult males
	Phosphate	Renal effects
Agricultural sources	Nitrite	Carcinogenicity
	Nitrate	Same as in nitrate above
	Sulphate	Same as in sulphate above
	Phosphate	Same as in phosphate above
	Chloride	Same as in chloride above
Natural sources		
Geological materials	Sodium	Convulsion, cerebral oedema
	Calcium	Cardiovascular risks
	Iron	Haemochromatosis
	Manganese	Neurological impairment
	Nickel	Haemianopsia
	Zinc	Diarrhoea, gastroenteritis
	Cadmium	Osteomalacia
	Potassium	Nausea, diarrhoea
	Alluminium	No known effects

In relation to this, Howard et al. (2003) and Cronin et al. (2004) carried out an assessment of urban groundwater quality in Mozambique and they established that the shallow groundwater quality had been compromised due to excessive proliferation of onsite sanitation systems in informal settlement areas.

In addressing these problems, Schmoll et al. (2006) stressed the need to identify the relationship between the above-ground anthropogenic activities and the underlying aquifers in urban areas. Also, Zaporozec (1994) argue that an assessment of the magnitude of the anthropogenic activities is important in making plans for a holistic risk assessment. Furthermore, Schmoll et al. (2006) uphold that appraising the potentials of urban pollution loading needs the understanding of the demographic densities in the various types of settlements across sub-Saharan Africa region. However, Forster et al. (2010), cautioned that the effect of the negative impact can be minimised by the local geology and confirms that this can vary greatly across the continent.

Likewise, agricultural activities are believed to be the major source of groundwater contamination in developing countries. In sub-Saharan Africa, many studies (Kelly and Ray, 1999; USEPA, 2002; Hallberg and Keeney, 2003) have investigated the impact of agricultural activities on groundwater systems. In this respect, Guan & Holley (2003), and Ross & Donnison (2003) reported that the excessive application of chemical fertiliser and other organic compounds have compromised the quality of groundwater resources across the sub-Saharan Africa region. Similarly, the impact of irrigation farming has been reported in the region (Hallberg and Keeney, 2003; Bolan et al., 2003; Dexcel, 2004; Mahvi et al., 2005).

Furthermore, groundwater contaminations due to industrial activities were investigated by various authors (Postma et al., 1991; Kelly and Ray, 1999; USEPA 2002; Smedana and Shiati, 2002). In view of this, a comprehensive list of industrial

processes and their effect on groundwater resources in Africa are documented by UNEP (1996).

Lastly, extensive discussions continue about the nature and type of damage contaminated groundwater can cause to human health, and the exact levels over which they pose health risks in Africa and other developing countries. This issue have been evaluated by many scholars (Burmaster and Harris, 1982; Calabrese et al., 1985; Hanley and spash, 1993; Fordyce, 2013; Seth, 2014).

2.8 Groundwater Sustainability in Sub-Saharan Africa

The issues concerning the sustainability of groundwater resources is reviewed and documented by Loucks (2000). Also, Loucks and Gladwell (1999) have identified the most common issues affecting the integrity of groundwater resources. Groundwater Sustainability signifies an optimal state of balanced recharge and abstraction (De Carvalho et al., 2009).

Also, Narasimhan and Kretsinger (2003) and Kretsinger and Narasimhan (2005) view sustainable groundwater management as the act of balancing withdrawal and recharge of groundwater in an aquifer with the intention of achieving long-term sustainability of the resource. This definition was corroborated by Nwankwoala (2011) in his analysis of the approaches to groundwater management in Nigeria.

However, authors such as Loucks (2000), Llamas et al. (2006), and Alley and Leak (2004) argue that realistic attempt to quantify the sustainability are not yet made clear in spite of the wide discussions in the scientific, academic and water management domains. In a related development, the Council of Canadian Academies (2009) and Knuppe (2011) note that the global groundwater governance policy makers needs to put in place a single bench mark that can be used in measuring the sustainability of water resources.

2.8.1 Sustainability-based Approaches for Groundwater Management

Major approaches to sustainable groundwater management includes; protection from depletion, protection from contamination, conjunctive use of surface and groundwater, artificial recharge, participatory governance, and adaptive management (Kinzelbach et al., 2003 Datta, 2005; Evans et al., 2008; Schwartz and Ibaraki, 2011). Each of these approaches are discussed in below:

2.8.1.1 Protection of Groundwater Supplies from Depletion

Sustainable groundwater management strives for the prevention of an uninterrupted and long-term reduction in groundwater quantity (Schwartz and Ibaraki, 2011). Therefore, safeguarding groundwater from exhaustion is a sustainable idea that requires striking a balance between the estimated recharge rate and the volume of water abstracted in an area (Datta, 2005). In this regard, most arid nations have developed policies that restrict the haphazard withdrawal of groundwater in

guaranteeing its sustainability. Once excessive depletion of groundwater occurs, the economic consequences will be severe; especially in arid and semi-arid regions (Galloway et al., 1999).

2.8.1. 2 Protection of Groundwater Quality from Contamination

Sustainability entails that groundwater quality is not conceded to substantial degradation of its physicochemical and biological characteristics (Kretsinger and Narasimhan, 2005). The consequences of poor groundwater quality can undesirably affect human health, fauna and flora, and the environment at large (WHO, 2006; 2011). Protection of groundwater contamination in rural and urban setting is a supportable model that seeks to ensure the safety of the citizenry and sustainable development (Schwartz and Ibaraki, 2011).

2.8.1.3 Conjunctive Use of Groundwater and Surface Water

The conjunctive use of water resources is an essential sustainability method of utilising water from two different sources for domestic consumption and other purposes (Evans et al., 2008). Therefore, the planned conjunctive use of the available water resources is an important sustainability model that provides socioeconomic benefits by significantly increasing water use efficiency for villages, towns and cities (Evans et al., 2008).

2.8.1.4. Artificial Recharge

Artificial recharge is a man-made recharge technique aimed at augmenting the quantity of groundwater through carefully designed engineering works intended to increase the volume of underlying aquifers for future use (UNEP, 1996). Groundwater recharge is a very important factor for ensuring sustainability of water resources in the arid and semi-arid regions of the world (Kinzelbach et al., 2003). Numerous artificial-recharge techniques and their applications are reviewed and documented in USGS (2010).

2.8.1.5 Participatory Groundwater Management

The inclusion and active participation of stakeholders in managing groundwater resources is an integral element of attaining sustainability (Garduno, 2010). Participatory groundwater management was clearly spelt out in the Dublin Declaration of 1992. Groundwater stakeholders are those individuals and a group of individuals who have a substantial interest in the resources base of a particular region. This is either because these individuals or group of individuals use groundwater, or their activities could potentially cause or prevent groundwater quality deterioration, or it is because they are concerned with issues associated with the governance of groundwater and the overall environmental management (Garduno et al., 2010).

Also, the participation of relevant stakeholders in the management of groundwater resources can occur at the various societal levels ranging from the single individual level to the regional or national level (Foster and Garduno, 2013). In view of this, Garduno et al. (2013) argue that stakeholder participation at all levels should be encouraged because it provides the desired protection for the underlying aquifers, and it ensures well-being of the citizenry.

Firstly, in any participatory groundwater management, stakeholders are identified and categorised. In this respect, a comprehensive list of stakeholder analysis methodologies are outlined in Friedman and Miles, 2006 and Reed et al., 2009. Also, Mitchell, Agle and Wood (1997) offer a model of stakeholder identification and salience based on the attributes of power, legitimacy and urgency. Furthermore, Philips (2003) distinguishes between normative stakeholders, derivative stakeholders and dangerous or dormant stakeholders.

Likewise, Sabrimanian and Siromony (2013) carried out a study in rural India on the need for stakeholder involvement in addressing problems of drinking water. Contrastingly, Knuppe and Pahl-wostl (2012) investigated three case studies in South-Africa, Kenya and Tanzania on the requirements for adaptive management of groundwater. They all stressed the importance of participatory groundwater management and summed up the challenges associated with it.

2.8.1.6 Adaptive Management of Groundwater Resources

The adaptive management approach is a philosophy that ensures sustainability of the water system (Pahl-Wostl, 2007). It allows societies and individuals to develop adaptive management capacities. The idea was first discussed and used in ecosystem management (Holling, 1978; Walters, 1986; Pahl-Wostl, 2007). The capacity to adapt and to shape change is an important component of resilience in social-environmental systems (Berkes et al., 2003). Adaptive management is frequently put forward as a realistic framework to deal with the complexity of ecosystem management and for optimal use and control of natural resources (Holling, 1978; Gunderson, 1999; Walket et al., 2004).

2.8.1.7 Ground water modelling as a tool for sustainable groundwater management

There is a growing interest in modelling groundwater resources in recent times (Sivapalapan, 2014). The MODFLOW MT3DMS (Modular Transport Three Dimension Simulator) is designed to simulate aquifer systems in which (1) saturated flow conditions exist, (2) Darcy's Law applies, (3) the density of ground water is constant, and (4) the principal directions of horizontal hydraulic conductivity or transmissivity do not vary within the system. These conditions are met for many aquifer systems for which there is an interest in analysis of ground-water flow and contaminant movement. Simple and complex numerical codes were developed by USGS (2010) to carry out groundwater modelling.

Darcy's law is a simple proportional relationship between instantaneous discharge rate through a porous medium, the viscosity of the fluid and the pressure drop over a given distance. It forms the scientific basis of fluid permeability used in earth sciences particularly in hydrogeology. It is based on the flow of water through beds of sand (USGS, 2002). Darcy conducted experiments relating to water's flow through sand, which resulted in the development of Darcy's Law (Figure 2.4).

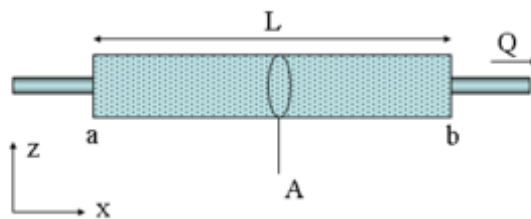


Figure 2.4 Darcy's experiment demonstrating water flow through sand (USGS, 2002)

Darcy discovered that the flow through the pipe is proportional to the head differential, and is also proportional to a coefficient related to the nature of the sand. This coefficient is what we now understand as hydraulic conductivity. Darcy's filtration law and continuity equation are applied to the solution of seepage by classical methods. For stationary, creeping, incompressible flow, Darcy's law is expressed as:

$$\mu \nabla^2 u_i + \rho g_i - \partial_i p = 0, \quad (1)$$

Where μ is the viscosity, u_i is the velocity in the i direction, g_i is the gravity component in the i direction and p is the pressure. Assuming the viscous resisting force is linear with the velocity can be written as:

$$-(\kappa_{ij})^{-1} \mu \phi u_j + \rho g_i - \partial_i p = 0, \quad (2)$$

Where ϕ is the porosity and κ_{ij} is the second order permeability tensor. This gives the velocity in the n direction:

$$\kappa_{ni} (\kappa_{ij})^{-1} u_j = \delta_{nj} u_j = u_n = -\frac{\kappa_{ni}}{\phi \mu} (\partial_i p - \rho g_i), \quad (3)$$

This gives Darcy's law for the volumetric flux density in the n direction as:

$$q_n = -\frac{\kappa_{ni}}{\mu} (\partial_i p - \rho g_i). \quad (4)$$

In isotropic porous media the off-diagonal elements in the permeability tensor are zero, $\kappa_{ij} = 0$ for $i \neq j$ and the diagonal elements are identical, $\kappa_{ij} = \kappa$, and the common form is obtained as:

$$\mathbf{q} = -\frac{\kappa}{\mu} (\nabla p - \rho \mathbf{g}). \quad (5)$$

The MODFLOW-2005 solves a fundamental governing equation using a specified numerical method. The Groundwater Flow Process is further subdivided into smaller units called packages. Each package solves a specific hydrologic process, while the solver packages solve the linear simultaneous equations that are generated by the application of the governing equation. The Groundwater Transport Process solves the solute transport equation (Konikow et al. 1996).

The modular structure of MT3DMS was used for simulating advection, dispersion/diffusion and chemical reactions within the modelled groundwater of the case study area. The chemical reactions included in the model are equilibrium-controlled or rate-limited linear or nonlinear sorption and first-order irreversible or reversible kinetic reactions.

The advection-dispersion equation is expressed as:

$$\frac{d}{dt} \int_a^b C(x, t) \omega A dx = Q(a, t) A - Q(b, t) A + \int_a^b F(x, t) A dx. \quad (6)$$

The term on the left-side is the rate of change of the total amount of contaminant in the section, and the first two terms on the right measure the rate that the tracer flows into the section at $x = a$ and the rate that it flows out at $x = b$; the last term is the rate that the tracer is created in the section. Because the interval of integration $[a, b]$ is arbitrary, the integrand must vanish and we obtain the mass balance law in the local, differential form as:

$$\omega C_t + Q_x = F. \quad (7)$$

Combining the constitutive relations with the mass balance law gives the fundamental reaction-advection-dispersion equation:

$$\omega C_t = (\omega D C_x)_x - V C_x + F. \quad (8)$$

If D is constant, then D can be pulled out of the derivative and can be written as:

$$C_t = D C_{xx} - v C_x + \omega^{-1} F. \quad (9)$$

Furthermore, the MT3DMS is implemented with an optional, dual-domain formulation for modelling the mass transport of the solute. This enables the porous medium to be viewed as consisting of two distinct zones, a mobile realm where transport is largely by advection and an immobile domain where transport is predominately by molecular

diffusion. Much detailed protocol; and step-by-step methodological approach can be found in Harabagh and McDonald (1988), Zeng and Kinzelbarch (2000).

The MT3DMS model has been globally accepted and applied in areas of contaminant transport modelling and remediation assessment studies. The key input parameters required by MODFLOW MT3DMS include;

- I. Transmissivity: is the amount of water that can be transmitted horizontally, such as to a borehole.
- II. Hydraulic conductivity: is the measure of geologic materials ability to transmit water when subjected to a hydraulic gradient. Hydraulic conductivity is defined by Darcy's law
- III. Storage coefficient: is the volume of water released from storage by a confined aquifer per unit surface area of aquifer per unit decline in hydraulic head normal to surface equal to product of specific storage and saturated thickness.
- IV. Vertical leakance: is defined as the average vertical hydraulic conductivity of the confining unit sediment divided by its thickness.
- V. Recharge: is primarily the infiltration of water into an aquifer. This process usually occurs in the vadose zone below plant roots and is often expressed as flux to the water table surface.
- VI. Maximum evapotranspiration: is the process by which water changes from a liquid to a gas or vapour. Evaporation is the primary pathway that water moves from the liquid state back into the water cycle as atmospheric water vapour.

MODFLOW/MT3DMS uses the above inputs to construct and solve equations of groundwater flow in the aquifer system. The solution consists of head (ground-water level) at every cell in the aquifer system (except for cells where head was specified as known in the input data sets) at intervals called “time steps.” The head can be printed and (or) saved on a computer storage device for any time step. Hydrologists commonly use water levels from a model layer to construct contour maps for comparison with similar maps drawn from field data.

Likewise, model outputs include estimates and prediction of parameters and statistics relating to the parameter estimates. The predictions of the models can be used as a decision support tool to take critical decisions in groundwater management. The statistics can also be used to quantify the reliability of the resulting model, suggest changes in model construction, and compare results of models constructed in different ways. Postprocessors can be used to calculate confidence intervals on predicted heads and flows to depict prediction uncertainty.

MT3DMS can be used to simulate changes in concentrations of miscible contaminants in groundwater considering advection, dispersion, diffusion and some basic chemical reactions, with various types of boundary conditions and external sources or sinks. The chemical reactions included in the model are equilibrium-controlled or rate-limited linear or non-linear sorption, and first-order irreversible or reversible kinetic reactions. It should be noted that the basic chemical reaction package included in MT3DMS is intended for single-species systems. An add-on reaction package such as RT3D (Harabough and McDonald, 2000) must be used to model more sophisticated multi-species reactions.

MT3DMS can accommodate very general spatial discretization schemes and transport boundary conditions, including: 1) confined, unconfined or variably confined/unconfined aquifer layers; 2) inclined model layers and variable cell thickness within the same layer; 3) specified concentration or mass flux boundaries; and 4) the solute transport effects of external hydraulic sources and sinks such as wells, drains, rivers, areal recharge and evapotranspiration.

Chloride was selected for determining the impact of pit latrine on groundwater because it one of the most the most commonly investigated chemical indicator of groundwater contamination from latrines; due to its high concentrations in excreta and its relative mobility in the subsurface (Graham et al., 2013). Even though there are no known health risks from chloride in drinking water, concentrations > 250 mg/L may affect the taste and acceptability of water (WHO, 2011).

2.9 Research Philosophy and Epistemology

This study employed a single case study research methodology with mixed-methods of data collection and analysis in one empirical research study (Kelle, 2006). Mixed-method research according to Preskill (2009) is the use of data collection methods both quantitative and qualitative which when collected will be richer, more meaningful, and ultimately more useful in addressing the research problem. In accordance with Benbasat et al. (1987) and Yin (2009) the study utilised the case study methodology to examine the problems of groundwater contamination in its

natural setting by employing both technical (quantitative) and social (qualitative) tools of data collection to gather detailed information.

Following Yin (1994) it is argued that the case study method is particularly suited to situations in which the researcher has little control over events or in which relatively little is known about the phenomenon under investigation. It has also been stated by Simons (2009) that a case study can have various perspectives i.e. the personal view of the researcher and its impact on the choice of the analysis and interpretation of how people think, feel and act through his own knowledge. The second is the story of the case i.e. how the researcher makes sense of a case study through understanding its underlying structure and meanings.

There is a misconception about the case study that it cannot provide reliable information but this has been refuted by Flyvbjerg, (2011) as case study has been defined by him as “detailed examination of a single example”. The case study enables the researcher to get valuable insight into and about the phenomenon under investigation. The strength and weakness of the case study as identified by Flyvbjerg, (2011) are summarised below (Table 2.6):

Table 2.6 Case study Method: Strength Versus Weaknesses (Source: Flyvbjerg, 2011)

Cases study methodology	
Strengths	Weaknesses
<ul style="list-style-type: none">• Depth• High conceptual validity• Understanding of context and process• Understanding of what causes a phenomenon, linking causes and outcomes• Fostering new hypotheses and new research questions	<ul style="list-style-type: none">• Selection bias may override or understate relationships• Weak understanding of occurrence in population of phenomena under study• Statistical significance often unknown or unclear

The author revealed that the research strategies can be used with any of the research/philosophical paradigms. For example, a case study research strategy can be interpretive, positivist, or critical. This study may be seen as utilising interpretivist approach as it employs qualitative methods, including person-to-person semi-structured interviews, and focus group for data collection and grounded theory (Strauss and Corbin, 1990) for data analysis, to gain understanding of stakeholder views and opinions. It also employs quantifiable measurement of survey data, geological and hydrogeological, and meteorological data to quantitatively evaluate the impact of anthropogenic activities on groundwater resources. But it does not have other positivist characteristics, such as aiming to develop universal laws.

Detailed analysis on epistemology is viewed and documented by many authors (Denzin, 1978; Hirschheim and Klein, 1994; Walsham, 1995; Klein and Meyers, 1999; Remenyi et al., 2002; Wyatt and Wyatt, 2003). However, as Klein and Myers

(1999) point out, research undertaken using qualitative methods may take a positivist stance; similarly, quantitative research may be interpretivist. The terms quantitative and qualitative should perhaps more appropriately refer to the methods used to generate and analyse data, with no epistemological assumptions implied.

2.9.1 Questionnaire design and developing the research questions

The design of the questionnaire evolved from the overall study context. In this respect, the research aim and objectives were reviewed, then statements and question items as outlined in Radhakrishna (2007) and Acharya (2010) were adopted. Details of the survey sampling strategy were described elaborately in this chapter (see section 3.3.5). Furthermore, research questions are the questions that a particular research is designed to address and guide the overall conduct of the study (Mason, 1996; Punch, 1998). The research questions of the study (see chapter 1, section 1.4) are both descriptive (what) and explanatory (how) in nature (de Vaus, 2001). They emerged from both literature review and the researcher's knowledge of the physical system of the case study area. In this respect, the study began with an extensive review of literature to identify gaps in relation to groundwater management in Africa. From the literature review, nexus of issues related to the overall aim of the study were identified, and then the researcher developed the research questions to investigate the causal factors of groundwater contamination in the case study area.

In view of the above, Tabor (2001) opined that this methodology is having great advantage; (i) the research questions will be well-grounded in obtainable studies, (ii)

there will be a coherence between the literature review and the overall aim of the study. Additionally, Mason (1996) argues that it is very important to differentiate between research questions and data collection questions.

Analysing data from qualitative study is increasingly becoming important in recent time. The study's findings in the social sciences aspect are based on: the opinion of stakeholders is acceptable across the social sciences (Mitchell, 2004). In this respect, many social science scholars (Arthur, 1994; Hudson, 1994; Campion, 1997; Huffcut et al., 2001; and Ployhart, 2006) argue that interview opinions are valid results that can be used to provide new strategies and are vital in developing new perspectives.

Also, finding based on interviews was reported by Vogwill (2016) as socio-hydrogeological tool for addressing groundwater challenges by local stakeholders and is a valid way of making decisions. Furthermore, the UN-Water (2015) and UN-SDGs (2015) are all in agreement with the findings deduced from stakeholder's opinion in developing a viable and sustainable framework. Taking these into consideration, the study is in agreement with the paradigm borrowed from the social sciences.

2.9.2 Hypothesis testing

Hypothesis testing is an important activity of empirical and evidence-based research. A well worked up hypothesis is half the answer to the research question (Smith et al., 2011). For this, both knowledge of the subject derived from extensive review of the literature and working knowledge of basic statistical concepts are desirable (Banerjee et al., 2009). In statistical hypothesis testing, two hypotheses are compared. These are called the null hypothesis and the alternative hypothesis (Landau and Everitt, 2004). The null hypothesis is the hypothesis that states that there is no relation between the phenomena whose relation is under investigation, or at least not of the form given by the alternative hypothesis (Strang, 2006).

The alternative hypothesis, as the name suggests, is the alternative to the null hypothesis: it states that there is some kind of relation. The alternative hypothesis may take several forms, depending on the nature of the hypothesised relation; in particular, it can be two-sided (for example: there is some effect, in a yet unknown direction) or one-sided (the direction of the hypothesised relation, positive or negative, is fixed in advance) (Philips, 2003).

According to Jacks et al. (1998) whether the null hypothesis is rejected and the alternative hypothesis is accepted, must be determined in advance, before the observations are collected or inspected. If these criteria are determined later, when the data to be tested are already known, the test is invalid. Likewise, Kelle (2006)

showed that hypotheses seldom sought disconfirmation of their favoured theories and they often ignore information that falsified their theories.

Other studies (Lord, Ross, and Lepper 1979; Jones and Russell 1989; Chapman and Chapman 1996) have shown the use of a single hypothesis leads to a bias in the way that people evaluate evidence. However, some authors (Gillis and Jackson, 2002; Johnson, 2004) are in disagreement with this position. Lastly, following the scheme in Benjamini (1995), this study formulated three different hypotheses (see chapter 4, section 4.3.3.2) and tests the relationship between socio-demographic and environmental variables.

2.10 Summary and conclusion

From the foregoing, it is evident that groundwater is a vital component of the hydrogeological system and is a precious natural resource in sub-saharan Africa where it serves more than 80% of the population. Naturally occurring and anthropogenic contaminants, high population and urban growth increasingly exert pressure on the quality of groundwater in this region.

The physical, chemical and geological characteristics of a hydrogeological environment play an important role in affecting the fate and transport of organic and inorganic contaminants in the subsurface. Sorption is the principal physical process that decreases the concentration of contaminants within the geo-system. Other physical processes that control the fate of contaminants include advection,

dispersion, straining, and particle-surface interactions. Furthermore, factors such as sediment grain size and mineralogy contribute tremendously in this regard. Adsorption is the principal chemical process occurring in the hydrogeological environment, it has the potential to eliminate toxic compounds within the subsurface thereby rendering them less harmful. Denitrification is the key biological process occurring in a typical sedimentary environment.

In another perspective, intricate linkage exists between groundwater management and environmental sustainability which is crucial for enhancing the quality of life of the citizenry. Protecting groundwater resources amidst the prevalent anthropogenic activities represent a substantial challenge that can lead to increasing costs of provision of drinking water in sub-Saharan Africa region. Therefore, it is imperative to align water resources management framework in this region within the context of the outlined sustainability based approaches herein. Also, current policies and approaches to groundwater management in this region need improvement; especially in dealing with environmental problems related to anthropogenic activities.

Likewise, top-down approach is the most dominant regime operated by most local, state and national agencies responsible for the management of groundwater resources in sub-Saharan Africa. Also, the institutions responsible for managing water resources require enhanced capacities to adopt and implement novel sustainable groundwater management policies. As outlined in this chapter (e.g. Howard et al., 2003; Cronin et al., 2004, UNEP and World Bank, 2000, and Pavelic

et al., 2013), huge gap exists in the sustainable management of water resources in sub-Saharan Africa. Also, if the existing system is not improved, the attainment of the SDG goal on the sustainable management of water resources will be difficult to attain in the next two decades

Also, existing methodologies and approaches of investigating the impact of human activities on groundwater resources at the river basin level (and their mitigation framework) is inadequate and are still evolving in most parts of sub-Saharan Africa. Most existing studies focus on the impacts of land use on the quantity and quality of surface water bodies thereby giving less emphasis to groundwater resources. Furthermore, other problems as outlined in the literature review, peculiar to this region include; exclusion of stakeholders in decision making, ineffective waste management, poor coordination and planning in the water sector, low level of capacity by the local water user groups to adopt new technologies, and the scarcity of scientific (geological and hydrogeological) data for planning. In this respect, the study adopts the participatory groundwater management approach to address the issue of stakeholder exclusion. This study applies the case study methodology that employs both quantitative and qualitative tools of data collection & analysis.

The study adopts the case study methodology addresses the existing gaps by carrying out a comprehensive assessment of the functioning of groundwater systems and their interactions with the numerous above-ground anthropogenic activities in the case study area. The justification for the adoption of the case study methodology

is because it allows the investigation of the coupled human-groundwater system including the physical and sociocultural dynamics in developing alternative groundwater management frameworks for sub-Saharan Africa region. Also, the case study methodology enables the understanding of circumstances and dynamic conditions of a complex system.

Likewise, the above-mentioned statement is aimed at achieving the overall objectives of the study; thus, it will apply the concept of socio-hydrogeology in the case study area to investigate the impact of above-ground anthropogenic activities on the underlying aquifers in a typical sub-Saharan African sedimentary Basin. Groundwater models have become decision support tools recently, the output of the modelling will be used to inform the alternative new guidelines of the study.

Lastly, the bottom-up approach envisioned by this study will address existing gaps by incorporating local knowledge and aspirations of stakeholders on the overall sustainability processes; this is essential for addressing the complex and highly interdependent groundwater contamination issues affecting societies and communities in sub-Saharan Africa. Specific recommendations for the sub-region are detailed in Chapter 8. The next chapter presents an assessment of the case study area.

CHAPTER 3

CASE STUDY AREA

3. Introduction

Chapter 2 provided a synthesis of the literature; this chapter presents the general features of the case study area and describes why a case study site is required to investigate the potential problems identified earlier. It provides vital information about the physical, human and environmental characteristics of the area. Also, it outlines the key environmental challenges facing the case study area. Specifically, it discusses the geographical, demographical and hydrogeological characteristics of the study area. The case study is a tool that can be used to investigate the potential contamination problems reviewed in chapter 2. Lastly, it summarises the key environmental challenges affecting the study area and how to address them. The chapter paves way for the subsequent analyses and discussions chapters in the thesis.

3.1 The Study Area

The case study area was selected to achieve the overall research objectives. Also, as outlined in chapter 1 (section 1.1), the justification for selecting the case study area is mainly guided by the geological, socio-economic, demographic, and environmental factors (Simons, 2009). Also, the case study area is chosen to identify

realistic societal problems and develop meaningful guidelines and recommendations in addressing these problems (Yin, 1994; Flyvbjerg, 2011).

The local case study area selected for this study is located in the Sudano-sahelian belt of North-eastern Nigeria. Generally, Nigeria covers a geographical area of about 924,000 km² between Latitudes 4° and 14° north and Longitudes 2° and 14° east. Sharing borders with Niger, Chad, Cameroon and Benin, the topography of the country ranges from mangrove swampland along the coast to tropical rainforest and savannah in the north. Figure 3.1 presents the location map of Nigeria showing the position of Maiduguri (the local case study area) in Borno state. The average rainfall in the country ranges from approximately 500mm/year in the extreme north to over 2,000mm/year in the extreme south. Most of the rainfall occurs during well-defined rainy seasons lasting four to five months (May to September) in the north and six to seven months (April to October) in the south.

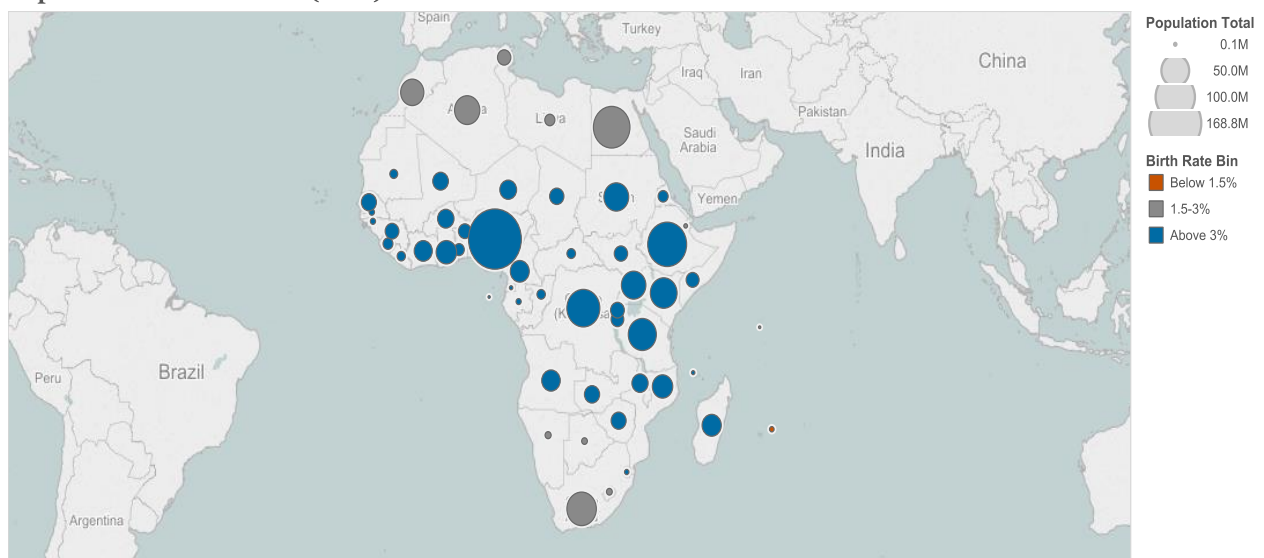


Figure 3.1 Map of Nigeria showing Maiduguri, Borno state (source, modified from VOA Maps online, 2014)

3.2 Demography

Nigeria is the most populous country in Africa with about 170 million people and an average density of about 135 persons per km² (World Bank, 2012). The population has been estimated by World Bank (2012), as growing at an average of 2.9% per annum in the study area and the sub-region (Figure 3.2), which is putting ever increasing pressure on the aquifer systems. The best estimate of the population distribution of the country (Table 3.2) indicates that the urban areas (major cities) have the greatest population followed by towns and rural areas (NPC, 2006).

Population and Birth Rate (2012)



Data Source: <http://data.worldbank.org/indicator/all>

Figure 3.2 Map of Africa showing annual population growth rate (World Bank, 2012)

Table 3.1 Population distribution by category in Nigeria (NPC 2006)

Population distribution category	Community size	Population (million)	% of total
Urban	>20 000	45	38
Small towns	5 000 to 20 000	40	33
Rural	<5000	35	29

According to the provisional figures from the 1991 census the study area (Borno state) has a total population of 2,596,589; and males outnumber females by 58,033 (NPC, 2006). The current projected population figures currently put the population of the state at 3,178,225 (BOSG, 2013). Average population density is only 46 persons per sq. km. (estimated at 52 persons per sq. km in 1999) (BOSG, 2013).

Taking into consideration the evidences presented (Figure 3.2 and Table 3.1) the case study area can typically represent the urban centres of the Sudano-sahel region of Africa. Thus, socio-demographic pressure and their resultant anthropogenic activities are prominent in this area as compared to others and hence their probable impact on groundwater resources.

3.3 Climate and Vegetation

Located in the semi-arid zone of north-eastern Nigeria, Maiduguri enjoys the warm tropical climatic condition of Western Africa. Most parts of the state fall within the Sudan savannah vegetation zone, whereas the far northern area falls within the Sahel vegetation zone.

Rainfall and other climatic conditions in Maiduguri are seasonal and affect greatly the local vegetation. The three distinct seasons: a long hot dry season from April to May. Day time temperatures are in the range of 36 to 40°C and night time temperatures fall to 11 to 18°C. This is followed by a short rainy season from May to September with a daily minimum temperature of 24°C and a maximum of 34°C with relative humidity of 40 to 65% and annual rainfall from 560 to 600 mm (Bakari, 2014). Finally, the cold (harmattan) season runs from October to March when temperatures fall to about 20°C and a dry dusty wind blows from the Sahara desert (Eugster and Maglione, 1979; Jaekel, 1984; Bakari, 2014).

The vegetation of the area is mainly of the Sudan and Sahel savannah type; which is characteristically dominated by woodland and shrub land dominated by annual grass species such as *Cenchrus biflorus*, *Schoenefeldia gracilis*, and *Aristida stipoides*. Species of acacia are the dominant trees, with *Acacia tortilis* the most common, along with *Acacia senegal* and *Acacia laeta* (Figure 3.3). This vegetation cover about 1000, Km (620 miles) across west and central Africa region (Eugster and Maglione, 1979).



Figure 3.3 Typical Sudano-sahel vegetation (source, Field trip)

3.4 Relief and Drainage

The landscape is developed on the young sedimentary rocks of the Chad Formation. This extensive plain contains no prominent hills and attains an average elevation of 300 metres above sea-level (Figure 3.4), sloping towards the Lake Chad level. The Borno region is drained by two groups of rivers; one is bound towards the south draining to the Benue system while the other is towards the Lake Chad (BOSG, 2014). The region is drained by seasonally flowing rivers whose peak flows are recorded during the rainy season in the months of July and August. The Biu Plateau to the south is largely drained by the Hawul River, which flows southwards and discharges its waters into the Gongola River. Also, the main rivers in Maiduguri are the Ngadda, Yedzaram and Gombole; their major sources are in the Adamawa highlands and Cameroon Republic.

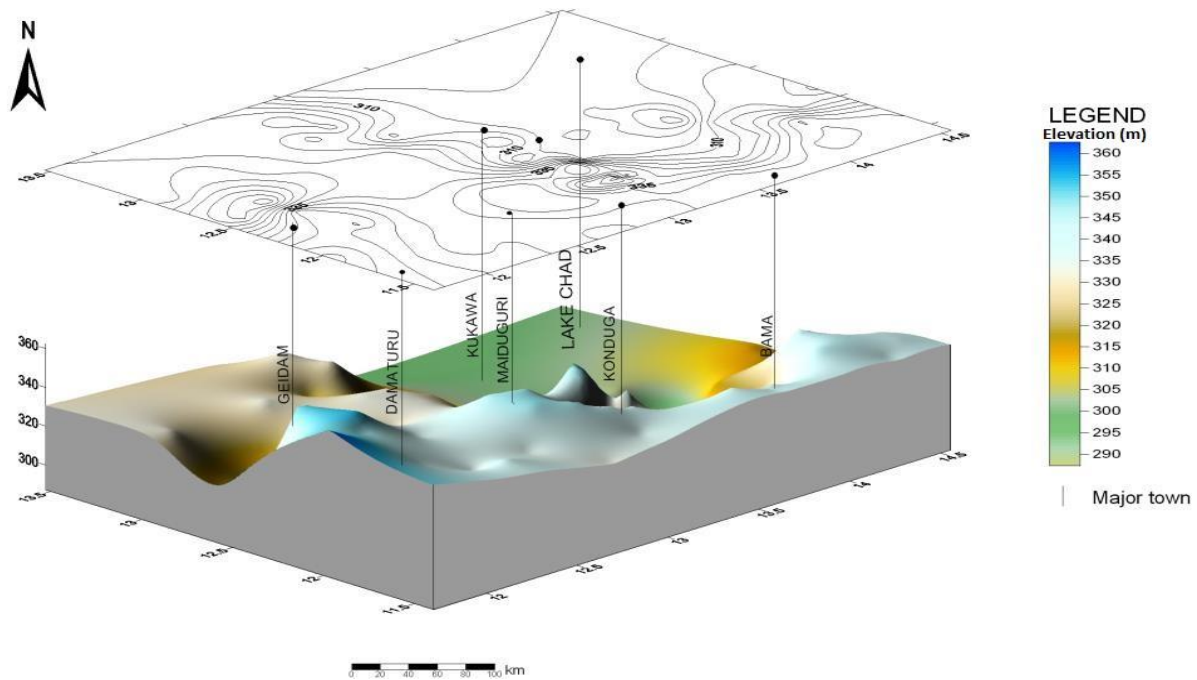


Figure 3.4 Model showing relief across the Nigerian sector of the Chad Basin (Aliyu and Bakari, 2014)

3.5 Geology and Hydrogeology of the Study Area

The Chad Basin has been a structural depression since early tertiary time and has been a locus of subsidence and sedimentation rather than erosion. According to Furon (1960) and Obaje (2009), the Chad Basin was a tectonic cross point between a NE to SW trending “Tibesti-Cameroon Trough” and the NW to SE trending “Air-Chad Trough” in which over 3600 m of sediments have been deposited (Bakari, 2014a).

The crystalline basement complex outcrops in the eastern, south-eastern, south-western and the northern rims of the basin; its configuration beneath the sediments near the lake has the semblance of a horst and graben zone (Oteze and Fayose,

1988). The stratigraphy of the Chad Basin (Bornu sub-Basin) shows a depositional sequence from top to bottom which includes the younger Quaternary sediments, Plio-pleistocene Chad Formation, Turonian-Maastrichtian Fika shale, the late Cretaceous Gongila formation and the Albian Bima Formation (Bakari, 2014a).

The Bima sandstone forms the deeper part of the aquifer series and rests unconformably on the basement complex rocks. Its thickness ranges from 300 to 2000 m and the depth between 2700 and 4600 m (Obaje, 2009). A pioneer investigation carried out by Barber and Jones (1960) revealed that the Chad formation reaches a thickness of at least 548 m at Maiduguri; in the central part of the basin the thickness may reach 600 to 700 m (Offodile, 1992). The Plio-pleistocene Chad Formation and the Quaternary sediments are the main sources of groundwater supply in the Maiduguri area (Bakari, 2014a).

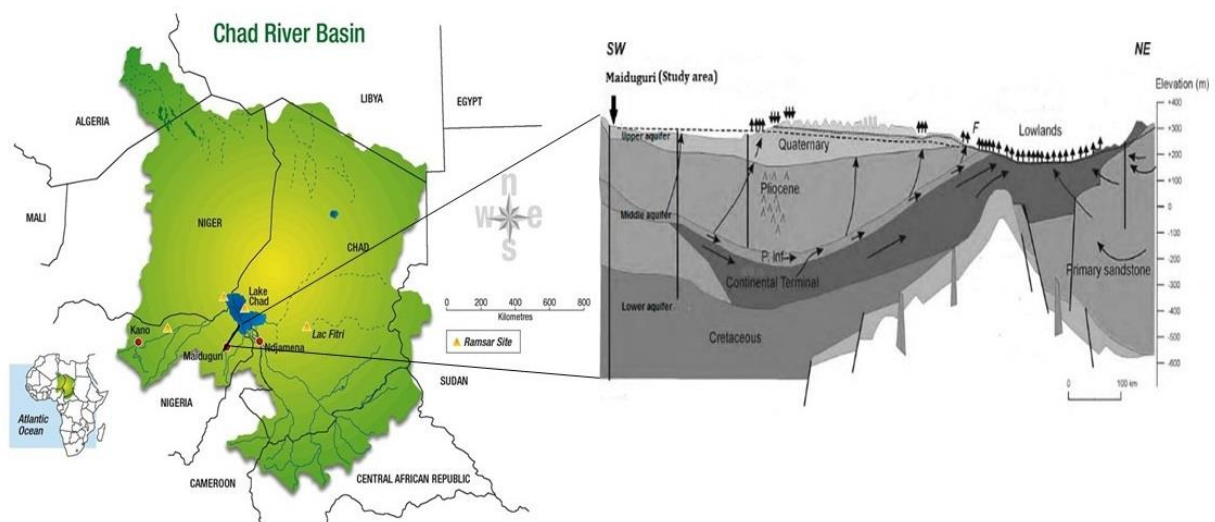


Figure 3.5 Cross section of the multi-layered aquifer system in Maiduguri (Modified from Shcoeniech, 1993)

The Chad formation dips gently east and northeast towards Lake Chad in conformity with the slope of the land surface. Except for a belt of alluvial deposits around the edge of the basin, the formation is of lacustrine origin and consists of thick beds of clay intercalated with irregular beds of sand, silt and sandy clay (Miller et al., 1968). As shown above (Figure 3.5), Barber and Jones (1960) divided the Chad Formation into three water bearing zones designated upper, middle and lower aquifers (Miller et al., 1968; Odada et al., 2006; Adelana, 2006; Bakari, 2014a).

The upper aquifer is a Quaternary alluvial fans and deltaic sediments of Lake Margin origin. The reservoir in this system is composed of interbedded sands, clays, silts and discontinuous sandy clay lenses (Table 3.2) which give aquifer characteristics ranging from unconfined, through semi-confined to confined types (Maduabuchi et al., 2006). It extends from the surface to an average depth of 60 m but locally to 180 m. The transmissivity of this aquifer system ranges from 0.6 to 8.3 m²/day and the aquifer yield in Maiduguri is between 2.5 to 30 l/s (Akujieze et al., 2003). This aquifer is mainly used for domestic water supply (hand dug wells and shallow wells), vegetable growing and livestock watering (Maduabuchi, 2006; Bakari, 2014a).

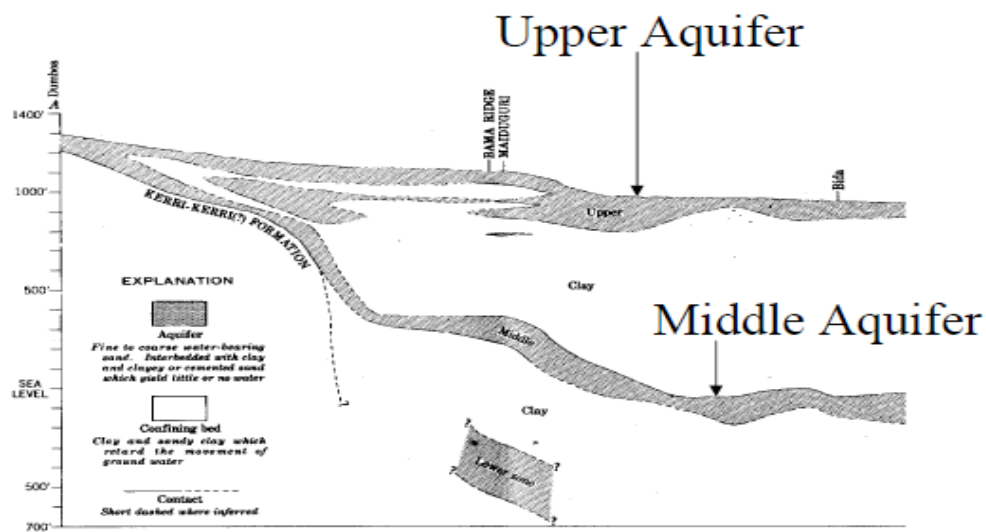


Figure 3.6 Cross-section showing the upper, middle and lower aquifers in Chad Basin (USGS, 2002)

The middle aquifer shown in the figure above is the most regionally exploited aquifer in the Chad Basin, especially in the Nigerian sector; it covers about 52, 000km² of north-eastern Nigeria. This aquifer lies at a depth between 317-393 m (Table 3.2) and made up of about 15-45m thick argillaceous sands with interbedded clayey units and diatomites of early Pliocene age (Miller et al., 1968; Bakari, 2014a). The sand materials of this aquifer are composed of medium to coarse grains of quartz, feldspar and mica. The transmissivity value obtained for this aquifer is 360 m²/day (Obaje, 2009). The aquifer yield is between 25 to 36 l/s (Akujieze et al., 2003).

Table 3.2 Representation of Borehole log showing upper, middle and lower aquifers in Maiduguri

Lithology	Thickness (metres)	Depth (metres)
Upper aquifer		
Sand, fine, yellow	7	9
Sand, fine to medium, yellowish	13	15
Sand, fine to medium, yellowish, thin clay layers	13	32
Clay, sandy beds, white	50	82
Clay, white to grey	13	94
Clay, grey to bluish grey	75	170
Clay, shaly, bluish; some thin lenses and fine layers	82	250
Middle aquifer		
Sand, fine to coarse, silty	14	317
Sand, fine, silty and firm	6.4	322
Sand, coarse	7.3	329
Sand, fine to coarse, silty	1	330
Sand, medium to coarse	4	334
Sand, fine to coarse, silty fine sand and clay layers	15	336
Sand, fine to coarse, a few very thin clay layers	4	350
Sand, fine to medium silty	10	354
Sand, coarse	1	364
Sand, fine to coarse, silty	22	365
Sand, fine to coarse	1.9	388
Clay, grey, hard	3	390
Clay, hard	5	393
Lower aquifer		
Clay, sand, clay	17	510
Sand, clay	10	524

(Reconstructed from Miller et al., 1968)

The lower aquifer presently found only in the Maiduguri area (Figure 3.6) , it occurs at greater depths exceeding over 500m and is made up of about 70 to 200m of interbedded clay, sandy clay, and sand (Table 3.2) (Akujize et al., 2003). A few thin beds of sandstone also occur in the zone. The chief water-bearing beds consist of

loose medium-to coarse-sand layers, generally about 1 to 5m thick. In some parts of the Basin, this aquifer is artesian in nature, and it is not abstracted for domestic water supply in greater part of the Chad Basin, its yield is between 10 and 35 l/s (Akujeze et al., 2003) and its recharge source is believed to be outside Nigeria (Goni, 2006).

Taking all the above into consideration, the study limited its investigation to the upper aquifer of the case study area. The justification for selecting this aquifer is based on: (i) it is unconfined in nature, thereby it might likely be affected by the impact of anthropogenic activities, (ii) it is widely used across the basin as the principal source of domestic water supply, and (iii) it occurs at a shallow depth, thereby wells and tube wells can easily tap water from it. These three parameters necessitated the study to limit its scope to the upper aquifer, in developing guidelines for their protection.

In Maiduguri, the likely sources of contaminants that may pose significant threat to groundwater quality is diverse and many. Much detailed assessment is presented in section 3.8. The pathways by which contaminants travel from the source includes spaces, poorly developed or abandoned wells, and fractures in the unconsolidated geologic material of the Chad Basin through which it flows into the aquifer and the receptors are the environment, people and animal drinking water from the aquifer (Bakari, 2014b).

3.6 *Status of Water Supply Provisions in Maiduguri Metropolis*

The provision of public water supplies (i.e. piped water connections) in Maiduguri metropolis is grossly inadequate and highly unreliable, as is the case in most other state capitals and cities in Nigeria (AICD, 2011). As a result, many urban dwellers are compelled to explore self-supply options, often without any form of treatment. Because many of the surface water sources in the region are seasonal (Bunu, 1999), groundwater sources remain the major focus of these self-supply options.

Across the metropolis, as in other parts of the country significant numbers of people rely widely on shallow wells (improved bore wells and hand-dug wells) for both commercial and domestic water use (Goni, 2006). This is because; it provides an affordable and easily obtainable alternative to the piped-borne system (UN 1988; BGS, 2003). However, it is increasingly reported by many authors, such as Foster *et al.* (2000), Wakida (2006) and Ali (2012) that groundwater aquifers in urban areas often deteriorate, especially in the urban centres of less-developed regions.

3.7 *Environmental Problems in Maiduguri Metropolis*

In Maiduguri, many of the challenges of environmental pollution arise from the diverse activities inherent to urban settings and are not being given proper attention as obtainable in most parts of Nigeria and across the Sub-Saharan Africa region (Maconachie, 2007). This is reflected in the apparent lack of accurate data and consistent information, as well as statistics on these issues even within the

responsible regulatory bodies. Many urban activities, such as SWM and sanitation services, are linked strongly to groundwater pollution.

The main concerns for groundwater pollution in the case study arise from anthropogenic activities (especially on-site sanitation systems). This is because the entire metropolis has no central sewage system (USAID, 2009). The situation likely represents serious diffuse pollution sources that could result in direct migration of pathogenic microbes to the local groundwater aquifers and beyond. Because raw sewage is often disposed of at the various open dump sites, it increases the risk of leachate generation and eventual contamination of groundwater aquifers. Another important source of groundwater pollution arises from urban agriculture.

3.8 Potential Sources of pollution in Maiduguri

Based on the observations carried out during the field work phase of the study, there are multitudes of anthropogenic and natural sources of contamination in Maiduguri metropolis. In this study, emphasis is on the anthropogenic sources of pollution. This is because of their potentials to contaminate the groundwater resources in the area due to increasing population growth. The probable natural sources of contamination are the materials found naturally within the rocks or sedimentary series of the Chad Formation; such as Quartz, Orthoclase feldspar, Microcline feldspar, Iron oxide, and Zircon which can become dissolved in ground water.

Anthropogenic contaminants originate from both point and non-point sources across the city. The point-source emanates from domestic and municipal waste disposal sites; others are industrial effluent from the various industrial activities in the city; though most of the industries are non-functional (Bakari, 2014). The wastes from these sources are mostly disposed in open spaces in bushes. Also in the informal settlement areas, the use of pit latrines is another major source of pollution. Furthermore, impacts from small businesses and other cottage industries can be remarkable. The potential risks and the contaminant types are summarised below (Table 3.3).

Table 3.3 Summary of potential risks and contaminant types

Potential risks	Contaminant types
Open dumpsites	Cl, NO ₃
Pit latrines	Cl, NO ₃
Agricultural activities	NO ₃ , PO ₄ , Cl
Industrial activities	Cl, SO ₄ , PO ₄
Petrol stations	Benzene, Xylene, Ethylene, and other Aromatic hydrocarbon compounds

Non-point-sources of pollution in Maiduguri are mainly the runoff and diffuse pollution from the agricultural activities near the lake Alau Dam where extensive irrigation and intensive fertiliser application is practised. Other potential non-point sources of pollution are the widespread commercial car wash areas, urban runoffs, etc. The potential sources of pollution are summarised in sections 3.8.1 to 3.8.5 as follows:

3.8.1 Open Dumpsites

Within Maiduguri metropolis, a huge amount of domestic wastes is generated on a daily basis by the various households depending on their socioeconomic status. Open dumpsites are the preferred sources of waste disposal (Figure 3.7). This is because most settlement areas lack adequate waste collection facilities. This can be seen in areas such as Gwange, Moduganari, Mafoni, Hausari etc (see map on Figure 4.3 in chapter 4).



Figure 3.7 Incessant solid waste disposals in residential area in Maiduguri

3.8.2 Pit Latrines and Septic Tanks

In Maiduguri, the use of pit latrines is very common because of its traditional attachment and affordability. Over 90% of the households surveyed utilise this system. The rapid urbanisation experienced in Maiduguri over the years has increasingly clustered the low-income individuals into informal settlements, thereby resulting in increased proliferation of pit latrines or increase in settlements with limited access to on-site sanitation facilities (Figure 3.8).



Figure 3.8 One of the open dumpsites in Gwange area in Maiduguri

3.8.3 Cattle Markets and Abattoirs

Abattoirs located within urban centres generate enormous amounts of wastes daily; in Maiduguri most abattoirs utilise traditional methods for the disposal of animal wastes, carcasses and manure. Also, cattle markets produce a lot of animal waste that are rich in nitrogen, in most cases these wastes are dumped indiscriminately.

Similarly, animal wastes generated from the slaughter houses or abattoirs are washed into open drainages untreated thereby introducing pathogens and excessive nutrients into surface waters that can subsequently percolate into the underlying aquifers and then contaminates groundwater. In this regard, there is only a handful of studies that focused on the impact of cattle market and abattoirs on groundwater quality in Nigeria.

3.8.4 Agricultural Activities

Various agricultural activities often result as point sources of groundwater pollution. The application of fertilisers, pesticides, and herbicides are a common agricultural practice, and they pose a significant threat to water resources across many regions of the world. These applications can be sources of contamination to groundwater supplies serving large populations. Whether or not fertilisers, pesticides, and herbicides become sources of groundwater contamination depends on the local hydrogeological conditions, application methods, and biochemical processes in the soil.

In Maiduguri, animal and human wastes are used as fertilisers; these have concentration of Nitrates and pathogens which are likely to pose a significant threat to groundwater quality. Currently, there are no existing studies that have evaluated the impact of agriculture on groundwater in the study area.



Figure 3.9 Irrigation farming in the Alau Dam area in Maiduguri

Extensive agricultural practices are common in the outskirts of the metropolis especially in areas such as; Bama, Dikwa, Biu/Damboa, Monguno and Kano Roads where sorghum, millet maize and groundnuts are cultivated. Also, sorghum and millet are cultivated on a large scale in the Lake Alau area (Figure 3.9); another crop that involves fertiliser application in the area includes; cassava, tomatoes, pepper, etc. Furthermore, cattle rearing activities are a common practice in some rural settlements in the outskirts of Maiduguri where the native Shuwa Arabs and Fulani cattle herders practise open ranch grazing.

3.8.5 Other Potential Sources of Groundwater Pollution

Other potential sources of pollution in the study area ranged from industrial activities to petrol stations and depots, and groundwater development activities. Therefore the study will carry out a qualitative risk assessment and prioritise the potential impact of these risks in achieving sustainable groundwater management.

For example, in the past, industries such as the Flour mill, the Coca-Cola bottling plant, and the Nitel shoe manufacturing company, the Borno plastic company, the Borno Aluminium smelting company, the Marini asphalt plant and the NNPC petroleum depot have operated in Maiduguri (currently not operating). In addition to this, other light and small cottage industries such as Block industries, bakeries, Hyde and skin processing and the traditional dying activities that use chemicals and their associated compounds are scattered across the city. All of these industrial activities are likely to impact the environment and groundwater resources negatively.

In the past, the effluent generated by all of the aforementioned industrial activities might have contained high concentrations of contaminants. The nature of the contaminant varies with the type of industrial activity, but usually includes chloride, nitrate, hydrocarbons or heavy metals, bacteria and viruses.

Moreover, Petrol stations are among the major sources of pollution in Maiduguri with potential risks to groundwater quality. A petrol depot and more than 60 petrol

stations exist in Maiduguri alone. Accidental spills or leaks from tanks and pipelines of petroleum products will impact negatively on the environment and groundwater resources. Some of the contaminants in such areas include phenols, aromatic compounds and chlorinated hydrocarbons.

Furthermore, pollution is likely to occur as a result of improper and poor groundwater development activities, for example, local drilling firms apply cheap synthetic drilling fluid in carrying out drilling activities. Some of the drilling fluids constitute synthetic compounds that might have an impact on the aquifer. Improper casing and well completion also allow contaminants to flow into the annular space which subsequently contaminates aquifers.

3.9 Pollution Sources Risk Assessment

From the contamination point of view, a risk matrix analysis outlined by Cox (2008) was adopted to evaluate the potential risks posed by the various above ground anthropogenic pollution sources on underlying aquifers in developing a mitigation framework that will alleviate their impacts on the underlying groundwater resources. In this regard, Table 3.4 presents the summary of the ranking based on the probability-impact matrix. This risk assessment methodology can be used by all the stakeholders to set priorities and protect the integrity of the groundwater. Also, they provide a clear framework for reviewing the risks of each of the contamination sources.

Table 3.4 Ranking of pollution sources based on risk matrix result

Pollution source	Likely impacts on groundwater			
	High	Moderate	Low	Very low
Pit latrine	●			
Dumpsites		○		
Agricultural activities			○	
Cattle markets				×
Geological material				×

3.10 Summary and conclusion

Maiduguri metropolis is the largest urban area in the North-eastern part of Nigeria; it falls within the Chad sedimentary basin attaining average elevation of 300 meters above sea level. Based on the socio-economic, climatological, hydrogeological, and demographic characteristics, the selected case study area can typically represent the urban centres of sub-Saharan Africa region. The city is moderate to densely-populated with high levels of anthropogenic activities. The study area lacks central sewage treatment system; hence, the inhabitants mostly use on-site sanitation facilities that are often poorly designed and regulated thereby raising concerns about groundwater contamination.

Groundwater resources are the principal water supply option. Major concerns for groundwater contamination arise from the urbanisation and agricultural activities in

the area. Of particular concern is the increasing utilisation of pit latrines and incessant waste disposal practice. Based on the qualitative risk assessment of the anthropogenic contamination sources, pit latrine is the one with the highest risk factor in terms of contamination, and then followed by open dumpsites, agricultural activities, and cattle markets.

To this effect, the challenges associated with groundwater management in the case study area is aggravated by many factors including the exclusion of the relevant primary stakeholders in planning, poor waste management, low level of institutional coordination and planning in the water sector, and the limited capacity of the various local water user groups to adopt new technologies (AICD, 2011). Also, groundwater quality in sub-Saharan Africa is severely threatened by impact of anthropogenic activities (World Bank, 2002). Widespread groundwater quality problems beneath African urban centres and rural areas are evident (WHO/UNICEF, 2000; AICD, 2011).

In the case study area, the potential sources of groundwater contaminants can be attributed to both point and non-point sources across the city. The point-source emanates from domestic and municipal waste disposal sites; the wastes from these sources are mostly disposed in open spaces in bushes. Also the informal settlement areas are a potential source of pollution. Furthermore, impacts from small businesses and other cottage industries such as dying, tanneries, and local brick making cannot be ruled out.

Non-point-sources of groundwater pollution can occur from the runoff and diffuse pollution from the nearby agricultural lands. This chapter presents background information of the case study area; chapter 4 outlines the methodology employed in the study.

CHAPTER 4

METHODOLOGY

4. Introduction

This chapter presents the design and methodology used in this study. It describes the various activities carried out in the research. Overall, the study divided into two major phases; the hydrogeological and social aspects. The hydrogeological category involves three key categories of activity: fieldwork; laboratory-based experimental and instrumental analyses and data analyses. Also, modelling was undertaken using MODFLOW computer codes to predict the trends of contaminants into the future. The social aspects of the study are also constituted of three major activities; stakeholder identification, stakeholder engagement (data collection), and thematic and content data analyses.

4.1 Quantitative strategy: groundwater quality analytical methods

4.1.1 Reconnaissance Survey

Three different field work activities were carried out between 2012 and 2014. The first field work was carried out between March and May 2012; during which detailed reconnaissance survey of the case study area (Figure 4.1) was carried out. During this period, topographical and geological maps were used to determine the local geology and the various land use activities of the area, as well as the extent of the case study area.

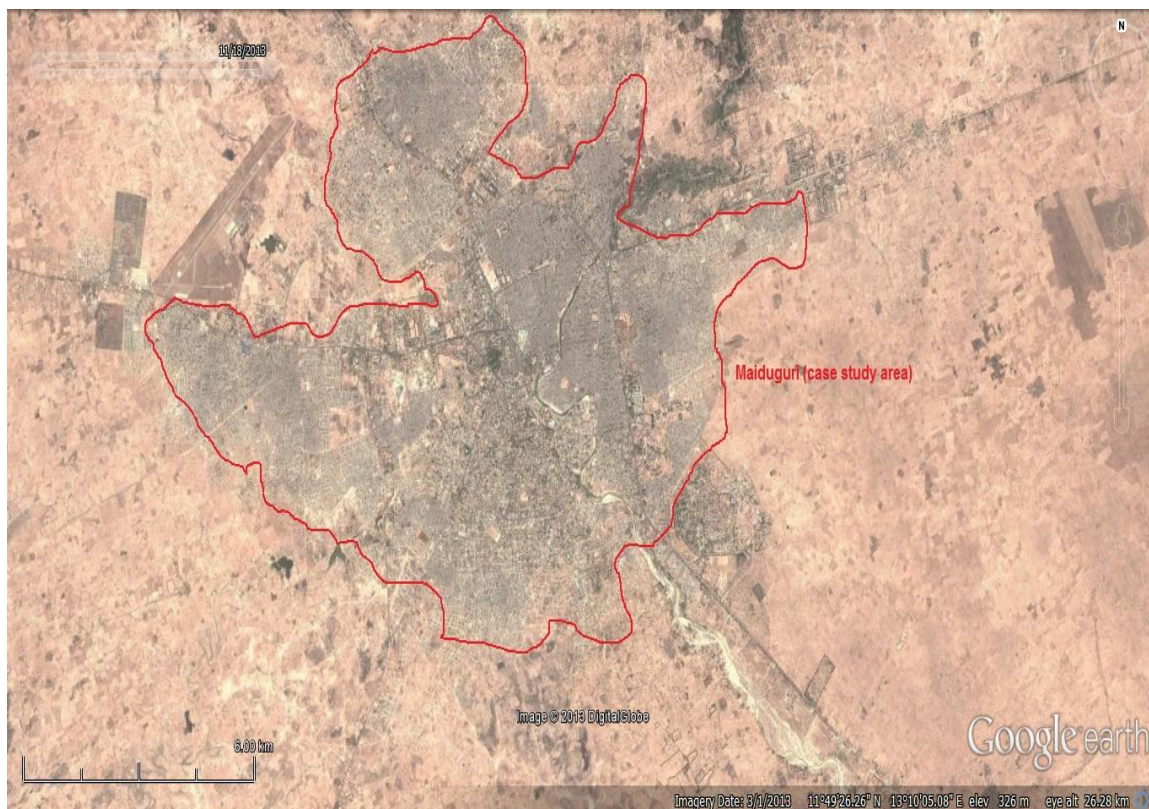


Figure 4.1 Map showing extent of Maiduguri metropolis (case study area)

4.1.2 Pollution Sources Identification

During the second round of field work in Maiduguri, the researcher in collaboration with a member of staff in the University of Maiduguri and 2 ad-hoc research assistants carried out a comprehensive inventory of pollution between January and February 2013. In this regard, the case study was divided into two major sites; in order to enable phased and detailed assessment of the aforesaid sources. In each case, detailed characteristics of the sites visited were recorded in the field log book. This allowed the conceptualisation of the system and practical linkages between the pollution sources and environmental degradation were established (Figure 4.2).

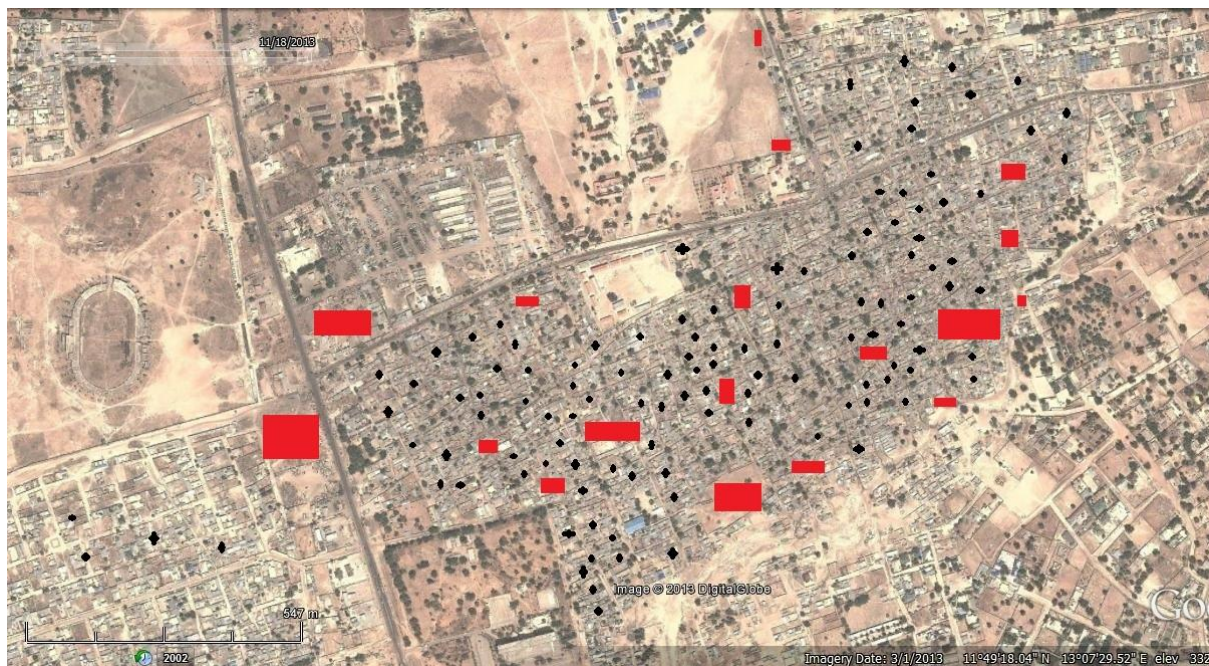


Figure 4.2 Aerial view of Moduganari area showing concentration of pit latrines and open dump sites (Google Map, 2012).

4.1.3 Selection of Groundwater Sampling Sites

Within the case study area, various groundwater supply sources (tube-wells) were surveyed; in this respect, tube-wells that meet the following criteria as outlined in the survey plan were selected:

- The borehole or tube well must tap water from the A zone of the upper aquifer (shallow).
- It must be within the residential area and serves a sizeable number of households (public).

Following the said criteria above, a total of 20 shallow tube-wells and hand pump boreholes were identified and marked for groundwater sampling in two major areas with the highest anthropogenic activities in Maiduguri (Figure 4.3). The location of each of these water points was recorded by a hand held GPS device (Table 4.1). All of the groundwater sampling sites were located across the case study area; this is to enable the detection of anthropogenic impacts within the vicinity of the boreholes/ tube wells.

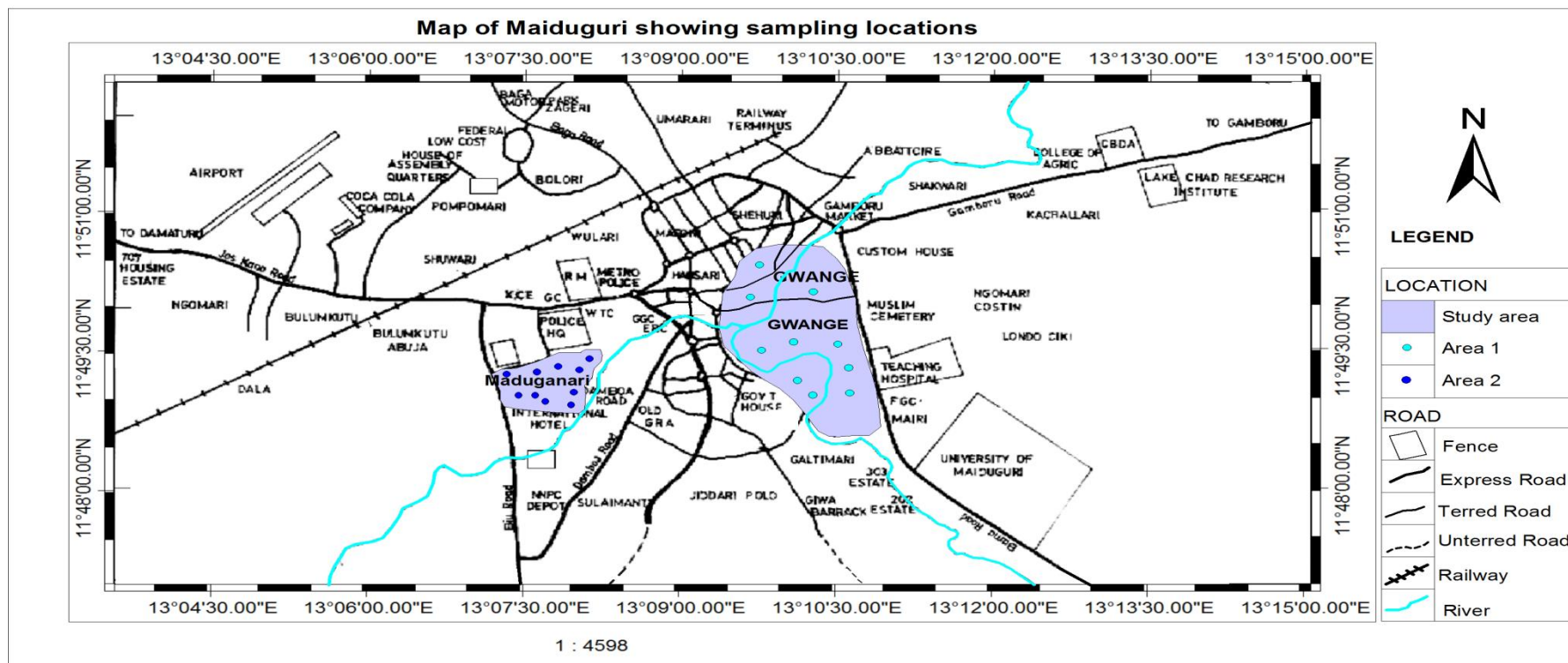


Figure 4.3 map of the study area showing the different sampling location

Table 4.1 Summary of borehole location in the two sampling sites

Sampling site/boreholes	Location coordinates
Borehole 1	N11°49.580' E013°07.675'
Borehole 2	N11°49.492' E013°08.994'
Borehole 3	N11°48.815' E013°08.361'
Borehole 4	N11°49.440' E013°07.602'
Borehole 5	N11°49.319' E013°07.061'
Borehole 6	N11°47.029' E013°06.021'
Borehole 7	N11°46.971' E013°07.897'
Borehole 8	N11°46.231' E013°06.101'
Borehole 9	N11°46.900' E013°06.425'
Borehole 10	N11°45.901' E013°05.215'
Borehole 1	N11°49.185' E013°10.633'
Borehole 2	N11°49.102' E013°10.312'
Borehole 3	N11°48.685' E013°11.203'
Borehole 4	N11°49.477' E013°10.733'
Borehole 5	N11°49.573' E013°10.551'
Borehole 6	N11°49.631' E013°10.616'
Borehole 7	N11°49.692' E013°10.731'
Borehole 8	N11°49.385' E013°10.133'
Borehole 9	N11°48.716' E013°10.878'
Borehole 10	N11°49.064' E013°09.883'

4.1.4 Experimental approach

In achieving the objectives of the Hydrochemical analyses of the study, the analytical techniques outlined in APHA (1998) and USGS (2010) were adopted to investigate the physico-chemical quality of the groundwater samples obtained across the study area. Table 4.3 summarises the various chemical analyses employed.

4.1.4.1 Onsite Measurements

The selection of the onsite parameters such as pH, EC, TDS and Temperature were based on the outlined procedure of USGS (2010). They are measured in the field due to their relatively unstable nature (USGS, 2010). The pH and temperature of the water sample were measured with a digital HANNA pH-meter (Model HI 98129). EC and TDS were measured with a portable conductivity, TDS and salinity meter (Model EC400 Ex Stik II). Summary of the error levels of the onsite measurement equipment used in this study as well as their precision comparison with similar studies are presented below (Table 4.2).

Table 4.2 summary of equipment error levels

Equipment	Error level	Precision comparison with other studies
HANNA pH meter	± 0.1 to 0.2 pH unit ³	USGS 2002, Stewards, 2011
Thermometer	$\pm 0.2^{\circ}\text{C}$	Singh, 2004, Edmunds et al. 2002
EC 400 (conductivity) meter	± 3 percent for EC, ± 5 percent for TDS	Jackson, 2013, USGS, 2010

4.1.4.2 Chemical Analyses

The groundwater samples (Figure 4.4) were analysed for chemical parameters such as; Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , NO_3^- , SO_4^{2-} , PO_4^{2-} , CO_3^{2-} , and CaCO_3 ions. The reason for selecting these cations and anions is because they are the potential natural and anthropogenic contamination indicator parameters in residential areas. Detailed justifications on these elements are documented in the APHA (2002) manual of water quality analyses.

Also, various experimental and instrumental techniques were employed to analyse the different chemical components. Summaries of these methods are presented in Table 4.4, while a complete description of the methods can be found in Standard Methods for the Examination of Water and Waste Water, 20th Edition (APHA, 1998) and USGS (2010) protocol for groundwater quality analysis. The physico-chemical analyses were carried out at the Geochemistry laboratory, the Department of Geology, University of Maiduguri.



Figure 4.4 some of the groundwater samples obtained for Hydrochemical analyses

Table 4.3 Summary of chemical analyses employed in the study

Chemical analyses	Methodology	Link with potential contaminant source
Calcium-EDTA Titrimetric method	50ml of the water sample was measured in a conical flask and then 2ml of 1N NaOH was added and mixed thoroughly. The solution was then titrated with 0.01N EDTA using peroxide indicator until the pink colour changed to purple at the end point, and the result was expressed in mg/l.	Natural hydrogeological environment
Magnesium-EDTA Titrimetric method	3ml of 5N HCl and 6ml Ammonia solution respectively were added, and then about 1ml of eriochrome black T indicator. The solution was then titrated with 0.01N EDTA until the wine-red colour changed to blue at the end point and the result was expressed in mg/l.	Natural geological material (hydrogeological environment).
Sodium-Flame Photometry method	Amounts of sodium in the samples were determined by a standard flame emission photometry procedure at a wavelength of 589nm. The result was expressed in mg/l.	Geological material
Potassium-Flame Photometry Method	Amounts of potassium in the samples were determined using a standard flame photometry procedure at a wavelength of 766.5nm. The result was expressed in mg/l.	Geological material
Nitrates-Brucine Sulphate method	10ml of H ₂ SO ₄ was added to the water sample and it turned brown in colour. The solution was boiled in a water bath and allowed to cool until a yellow colour was developed. Potassium nitrate was used as a standard. The colour was then read using a colorimeter at a wavelength of 410nm, and	Nitrate is linked to the widespread anthropogenic point-source pollution sources such as the widespread open dumpsites, pit latrines, tanneries, Hyde and skin processing and the uncontrolled domestic wastewaters emanating from the cluster of informal residents in both the study area, as well as

	the result was expressed in mg/l.	the agricultural inputs from upstream manure application in farm lands.
Chloride-Argentometric Method	100ml of the water sample was measured, and 1ml of potassium dichromate ($K_2Cr_2O_7$) was added as an indicator. The solution was then titrated against 0.01N Silver Nitrate ($AgNO_3$) solution until the yellow colour changed to brown at the end point, and the result was expressed in mg/l.	Chloride is linked to the widespread open dumpsites and waste water flowing uncontrollably in the informal settlements of the study area.
Sulphates-Gravimetric Method	250ml of the sample was measured, and its pH was adjusted with 1N HCl to about 5, using a pH meter. It was brought to a boil while slowly adding barium chloride solution and stirring gently until precipitation appeared to be complete. The precipitate was digested at about 80°C to 90°C for 2 hours. The precipitate was filtered with filter paper, washed with distilled water and placed in a crucible along with the filter paper, and then heated in a muffle furnace at 800°C for 1 hour. It was allowed to cool in a desiccator, and the barium sulphate precipitate weighted.	Attributed to domestic wastes and decomposition of organic matter, sometimes emanates from industrial wastes, but mostly from the bacterial reduction of sulfate. Others are tanneries
Phosphate	The result was expressed in mg/l To 100-mL sample add 0.05 mL (1 drop) phenolphthalein indicator solution. If a red colour develops, add strong acid solution dropwise, to just discharge the color. Then add 1 mL more. Boil gently for at least 90 min, adding distilled water to keep the volume between 25 and 50 mL. Cool, neutralise to a faint pink color with NaOH solution, and	They are found in sewage from body wastes and food residues, and also may found as orthophosphates in agricultural and residential areas.

restore to the original 100-mL volume with distilled water.

Carbonate and Bicarbonate

25 to 50 mL of the sample was measured in a conical flask, and its pH was adjusted to 4.3 about 2 to 3 drops of phenolphthalein indicator was added. H_2SO_4 was standardised against 40.00 mL 0.05N Na_2CO_3 with about 60 mL distilled water, in a beaker by titrating potentiometrically to pH 5. The electrodes were lifted out, rinsed into the same beaker and boiled gently for 3 to 5 min under a watch glass cover. It is then allowed cool to room temperature; cover glass rinsed into beaker and titration finished (pH 4.3). The result was calculated and expressed in mg/l.

Geological material

4.1.5 Sediment Sample Collection

As outlined in Bakari (2014c), representative sediment samples (sandstone and siltstone units) that constitute bulk of the Quaternary Chad formation were systematically collected at two varying depths of 5 and 10 metres in two different locations (sites 1 and 2) respectively. Simple hand held auger and sampling tools such as shovel, digger, plastic bucket, polyethylene bags, and measuring tape were used. This method is adequate for carrying out preliminary investigations on superficial deposits (USGS, 2010).

Hand augering was carried out at systematic depths of 5 and 10 m respectively, at each depth about 1kg of the sediment sample was collected, the sample is then divided into 2 portions (for granulometric and mineral content analyses) and poured into a properly labelled plastic bucket in each case. This procedure is repeated at the depth of 10 metres and in site 2. All the samples were transported to the sedimentary petrology laboratory at the Geology department, the University of Maiduguri for analyses.

4.1.5.1 Sieve Analysis

The portion of sediment sample retained on the No. 10 sieve is tested for grain size distribution by passing the sample through a number of sieves of different size openings as outlined by ASTM D (2000). The sieves are stacked in order, with a

sieve with 2 mm aperture size at the top. The sieves are agitated by mechanical means for about 10 minutes. When this mechanical process is completed, the weight of the particles retained in each sieve is determined using the Ohaus (Model T31P) digital balance, from which the individual and cumulative percentage weights were computed (Bakari, 2014c).

4.1.5.2 Mineral Content Analysis

The required amount of sediment sample with constant size was separated in the plastic bag, debris and organic matters were removed. Then, the samples were spread out carefully on a picking tray in such a way that particles do not overlap with one another. A magnifying microscope (Model WestburySP40) was used to observe, identify and count the various minerals in the sample based on their physical properties. Four specimen slides were prepared for each sample and the percentages of each mineral was calculated separately. Also, average percentage of each mineral was calculated from the aforesaid calculations (Bakari, 2014c).

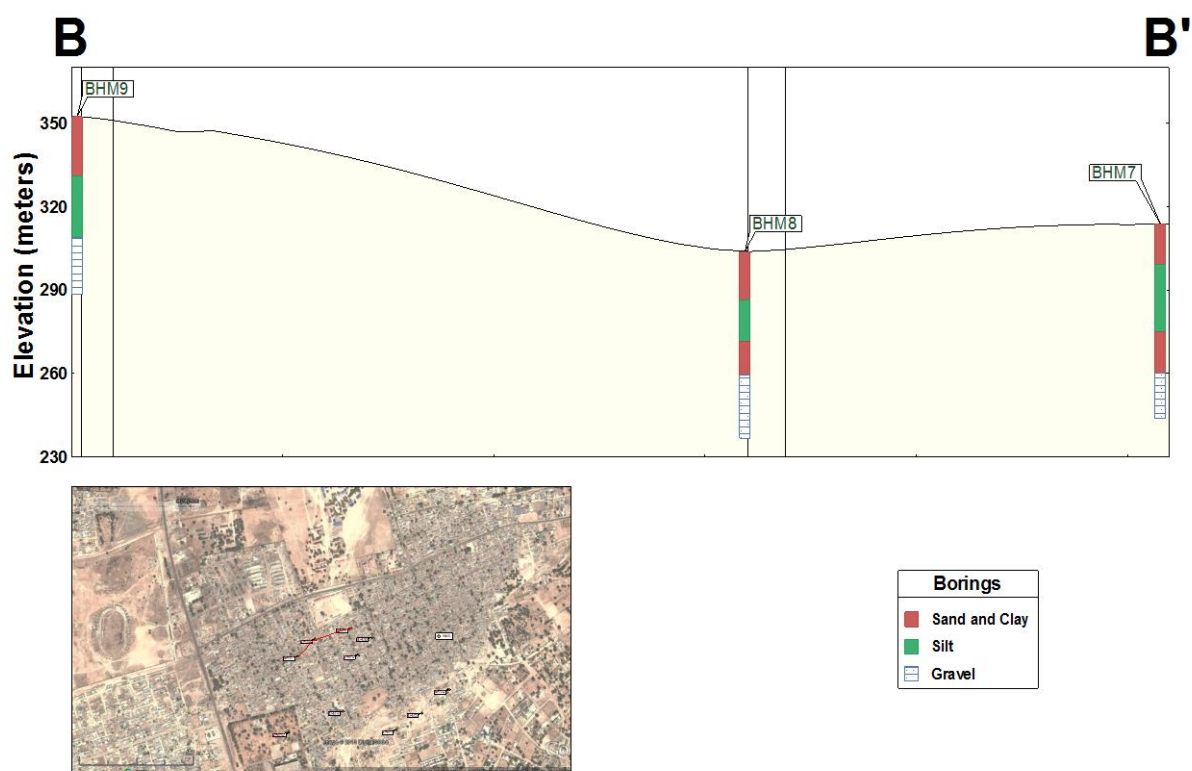
4.1.6 Hydrogeological Model Data

A total of 20 shallow boreholes log data covering the study area was obtained from local drillers. The raw data was entered into Microsoft Excel spread sheet based on the sub categories outlined in Table 4.4.

Table 4.4 Summary of data requirement for EnvironInsite hydroanalysis

Table	Fields
Wells	Name, location, surface/bottom elevation, class
Screens	Well/screen name and bounding elevation interval
Observations	Well/screen name, measured value, date, constituent
Constituents	Analyte, units, media
Borings	Well name, soil or boring log description, top/bottom depth
Stratigraphy	Well name, strata, top/bottom elevation or depth
Fill	Material, top depth, bottom depth

The data are analysed using a special hydro-analysis software (EnvirolInsite 2013 ©) for developing 2D cross sections of the boreholes (Figure 4.5) and 3D visualisation of the aquifers of the study area (Figure 4.6).

**Figure 4.5 2D cross section (B-B') showing boreholes 9, 8, and 7 in Moduganari area**

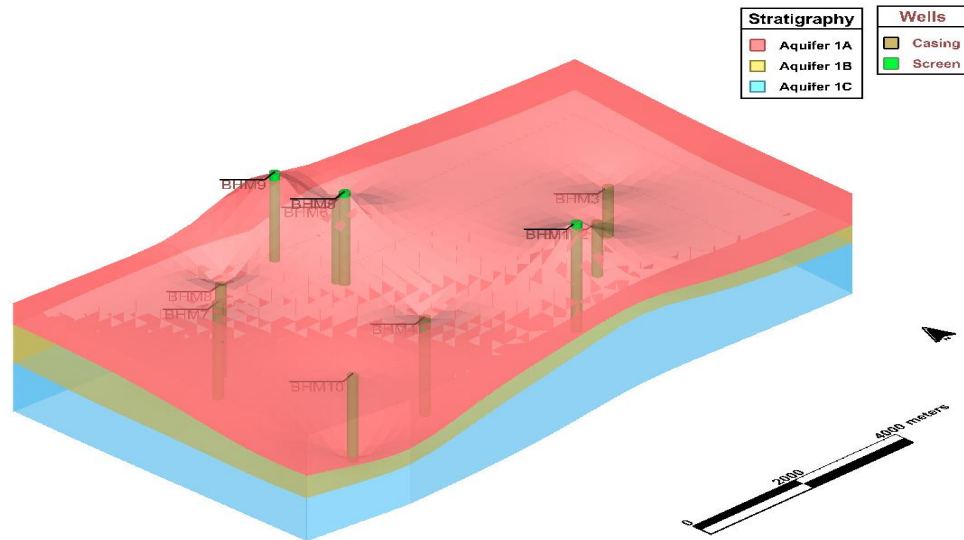


Figure 4.6 3D Conceptual representation of the upper aquifer in Maiduguri

The conceptual model above (Figure 4.6) provides information about the borehole depths and aquifer characteristics. The physio-chemical parameters of interest are outlined in detail in chapter 5 (sub-section 5.7.1.3).

4.2 *Qualitative Strategy: a Social Dimension*

4.2.1 Stakeholder Analysis

The analysis adopted for this study considers the empowerment of grass root individual groups, such as groups of youths & women, and those without access to well-established social networks, the under privileged, or the socially disadvantaged (Johnson et al., 2004).

In this study, analytical categorisation method was adopted. This is due to its suitability of allowing the researcher to categorise the stakeholders based on his understanding of the system and the prevailing situation in question (Hare and Pahl-Wostl, 2002; Reeds et al., 2008). In addition, it also saves the researcher's time and resource as opposed to the reconstructive categorisation method. The analytical tools used in categorising the stakeholders include those using levels of interest and impact (Lindenberg and Crosby, 1981; Hare and Pahl-Wostl, 2002), legitimacy and influence (Mitchell et al., 1997). A stakeholder analysis was carried out from the beginning of the study in 2012 to identify the various stakeholders that will address the current, emerging, and future problems of groundwater management in the case study area.

Hare and Pahl-Wostl (2002) argue that there is no limitation to the number or categories of stakeholders in the analysis, but their number is determined by the prevailing situation. In this respect, a total of 6 different stakeholder groups

consisting of 22 individual groups and organisations; which consists of civil society organisations, NGO, Government ministries/agencies, and a research institution were identified. Others include group of professionals, traditional rulers and politicians as shown in Tables 4.5, 4.6, and 4.7. This number (group of stakeholders) is adequate (Mitchell et al., 2004). Also, the reason for selecting these stakeholder groups is because they are the ones directly affected by the problems of groundwater contamination, and are capable of providing lasting solution in the study area. The representatives of the various stakeholder groups were engaged via interviews, focus group discussions, and stakeholder meetings (McNamara, 1999; Morgan, 1997; Patten, 2001).

The well-educated stakeholders were engaged via semi-structured interviews using English language while the residents and other water users were engaged via focus group discussions using the two dominant local languages *Kanuri* and *Hausa*. English language was used to engage the institutional stakeholders (government officials) because it is the official language in the public domain. The native languages were used for the local water users and residents due to their low literacy levels.

Table 4.5 Stakeholder Categorisation as primary, secondary and key (After Frooman, 1999)

Primary stakeholders	Secondary stakeholders	Key stakeholders
Local residents	BOSG	Local residents
Public water users	MMC	Public water users
Farmers union	BOHA	Farmers union
Local enterprises	BOSEPA	Local enterprises
	Ministry of water res.	BOSG
	Ministry of Education	Ministry of Education
	Ministry of Health	MMC
	Ministry of Agriculture	BOHA
	Urban Development Board	BOSEPA
	Lake Chad Basin	Ministry of water res.
	Commission	
	University of Maiduguri	Ministry of Health
	National union of Journalists	Ministry of Agriculture
	Nigeria union Teachers	Urban Development Board
	UNICEF/WHO	Lake Chad Basin
		Commission
	Friends of Lake Chad	University of Maiduguri
	Manufacturers Association	National union of Journalists
	Council of traditional rulers	Nigeria union of Teachers
		UNICEF/WHO
		Friends of the Sahel
		Manufacturers Association
		Council of traditional rulers
		Borno youth forum
		Borno women forum

Table 4.6 Summary of the various stakeholder groups in the study area

Organisation Type	Number of groups
Government ministries/ agencies	10
Water user groups	4
Professional organisations	3
Civil society organisations	3
NGO	1
Research institution	1

4.2.2 Interviews

Interviews are very useful, particularly for getting the story behind participants' experiences. The interviewer, according to McNamara (1999), can pursue in-depth information around the topic and can be useful as follow-up to certain respondents to questionnaires with a view to investigating their responses.

Interviews, according to Fontana and Frey (2005), can be divided into three categories, viz: structured interviews, semi-structured interviews, and unstructured interviews. Semi-structured interview is relatively more flexible than a structured interview, and it consists of both closed-ended and open-ended questions (Fontana and Frey, 2005).

During the field work conducted in March to July 2013, a semi-structured interview with certain flexibility was conducted with the key stakeholders identified in the stakeholder analysis. A total of twelve strategic stakeholders as representatives of their organisations; one each from the eight government ministries/ departments & agencies and the municipal council, one research institution, a non-governmental organisation and the one civil society groups were interviewed from April to June 2013 (Figure 4.7).



Figure 4.7 Interview with some of the strategic stakeholders

Table 4.7 Summary of strategic stakeholders interviewed and their affiliations (after Reeds et al., 2009)

Stakeholder	Affiliation
Director groundwater services	Ministry of water resources
Deputy director sanitation	Borno state environment protection agency
Director engineering services	Borno state Urban development board
Assistant Director	Ministry of Education
Senior staff	Ministry of health
Senior staff	Ministry of environment
Council secretary	Maiduguri metropolitan council
Staff member	Borno state house of assembly
Senior lecturer	University of Maiduguri
Coordinator	Friends of the Sahel
Chair woman	Forum of women
Hrdrogeologists	Chad basin development authority

The researcher interviewed the strategic stakeholders on a one-on-one format in their various offices and exceptional few in their homes. Prior to the interview; appointments for the interviews were requested and booked by telephone calls, texts messages and personal visits. At the first contact with the interviewees, the researcher explained the purpose of the study and why he or she was identified as a potential interview candidate. After this step, permission to be interviewed at their

convenience were sought; at this stage a copy of the research protocol and introductory letter approved by the Abertay University was made available to the interviewee in advance of the slated date. The interview questions were not disclosed to them at this point, because this will influence the level of stakeholder responses during the interview.

4.2.3 Pre-focus Group Capacity Building Workshops

The researcher carried out a pre-focus group capacity building workshops (Figure 4.8) for the primary stakeholders taking into account their level of education and limited capacity. These stakeholders are comprised of the local residents, group of small scale farmers, and local business owners (Johnson et al., 2004).



Figure 4.8 Pre-focus group capacity building workshop in the case study area

The objective of the capacity building workshop was to increase the awareness level of the stakeholders and to provide them with a simplistic overview of the complex physical and hydrogeological systems and how each of these systems is affected by their activities, to identify a strategy that will contribute to sustainable management of groundwater in the context of an IWRM approach in the case study area, and to develop a coping strategy that will mitigate future uncertainties of climate change, and urban & population growth.

The decision support tools used include simple illustrations showing the relationship between pollution sources, pathways and the underlying groundwater. Vulnerability maps were produced from the water quality result obtained. This is because such maps are simple and an essential tool for better understanding of the resources base, and in making informed decisions. Overall, the capacity workshops have provided better understanding of scientific processes to the marginalised stakeholders, and on how the interaction with the physical system affect the quality of the groundwater resource.

4.2.4 Focus Group Discussions

Focus group discussions were chosen as a method to provide a forum for primary stakeholders as water users to discuss their concerns, understanding and opinion towards groundwater management issues in the study area. Focus group discussions have the advantage of allowing a lot of data to be collected in a short period (Morgan, 1997). They allow the researcher to develop an understanding

about why people feel the way they do, participants are able to bring up issues they feel are important to them, and are able to challenge each other's views and the researcher may benefit by having a more realistic account of what people think of the current system (Miller and Glassner, 1997; Morgan, 1997). Focus groups are also an effective way of advancing a study subject (Madriz, 2003).

A total of six (6) focus group discussions were conducted with the local water user groups on the potential two sites of the study area. The focus group discussions were held across the different communities of sites 1 and 2 (Moduganari and Gwange areas) respectively. In total there were 52 individuals; 40 males and 12 females drawn from the local residents and water user groups as well as groups of youths; this is because they constitute majority of the population, and they can provide valuable contributions to the research questions (Graiser, 2008).

Each focus group comprised of about 8 to 9 residents from each of these communities. According to Krueger and Casey (2000), the ideal size of a focus group for non-commercial research ranges from six to eight. To increase representativeness, the participants were drawn by random sampling from different walks of life; this selection is based on a combination of demographic information and professional guidance tool.

The focus group discussions were carried out at the community level the; participants were contacted prior to the meeting, purpose of the study and the

significance of their contribution were highlighted at this point. Two research assistants were hired among the local community members for the duration of the focus group discussions. A copy of the research protocol and introductory letter approved by Abertay University was made available to them. Participants were also informed of the meeting time and place at this point.

The researcher also made it clear to the participants that refreshment will be provided at the meeting, and a token of £2 (N500) will be available for reimbursement to cover their transportation costs. The focus group discussions took place within 5KM radius of the residences of participants; the aforementioned token is sufficient for fares within this radius.

On the day of the focus group discussion, the researcher briefed the participants about the purpose of the study and why their contribution is important to the study. The researcher made sure that participants were aware that there are no wrong or right answers during the focus group session, and the ground rules for discussion were clarified for the participants (Figure 4.9).



Figure 4.9 Focus group discussions with some participants in the case study area

Each participant was given generous time to express his or her opinion. In a rare occasion where one or more participants tried to be domineering in the discussion, the researcher neutralises the discussion and stresses the need for others to contribute their views (Casey, 2000). Each of the sessions was chaired by a moderator with two assistants; responsible for audio recording of tapes and note taking respectively. The sessions formed open discussions where questions were thrown to participants for debate.

4.2.5 Household Survey

This method of data collection is considered as one of the most efficient methods of data collection from a large sample (Saunders et al., 2003). A questionnaire can either be structured, semi-structured or unstructured. This study adopted structured questionnaire that consists of pre-coded questions with well-defined patterns to

follow the sequence of questions. According to Acharya (2010) most qualitative data collection, activities use a structured questionnaire. Structured questionnaire has the advantage of being easy to administer, consistency in answers and easy for data management (Acharya, 2010).

Stratified systematic sampling was used in identifying the various households for the study. Patten (2001) argues that, when this method is used properly, systematic sampling produces a sample that is as valid as a sample obtained using simple random sampling. A respondent was identified in every third house at the two sites (Moduganari and Gwange) of the case study area; participants were selected based on the sub divisions of the study area. For instance, the potential sites (Moduganari and Gwange) were selected based on their socio-economic and demographic context. Thus, these divisions were taken into consideration to ensure that respondents were drawn to represent the various households of the study area. Unlike the personal interviews and focus groups, the survey method allowed efficient data collection from a larger sample of the residents in a relatively sensible manner.

A total of 600 household questionnaires (Figure 4.10) were distributed for 600 households (300 each) in Moduganari and Gwange. In total, 81 % response rate was achieved for both sites. Also, a follow up survey on the vertical and horizontal depths of on-site sanitation systems and water levels and points were administered in the same manner as stated above. The rationale for carrying out the follow-up survey is to provide support for the development of realistic and sustainable guidelines that will

mitigate the impact of the onsite sanitation systems on the local aquifers of the case study area. This provides a framework within which practical solutions of achieving sustainable groundwater management can be implemented; in line with the overall aim of the study.

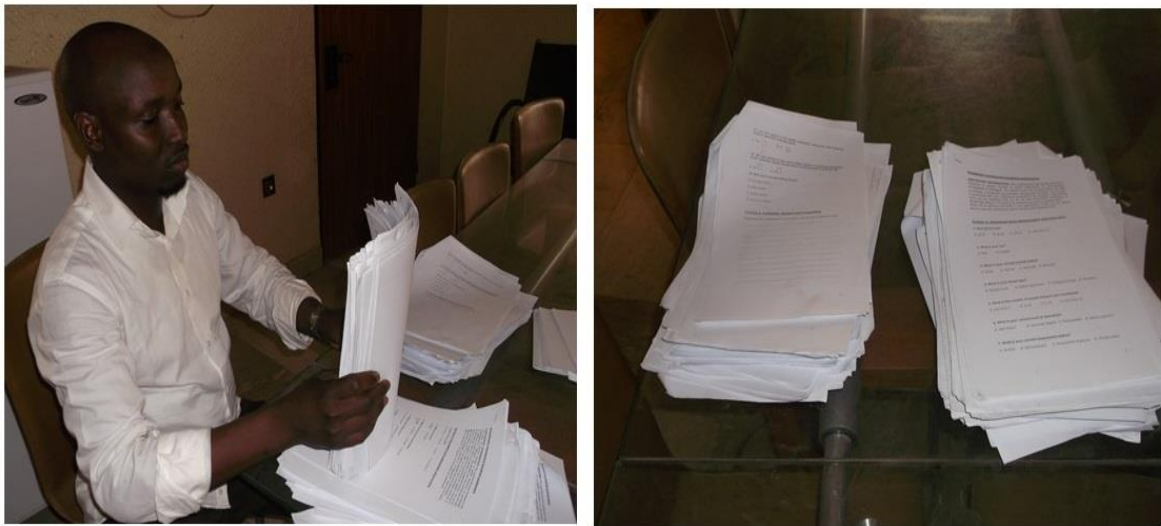


Figure 4.10 the researcher sorting out the filled household survey questionnaires

Since the centre piece of this study is focused on low income individuals (urban poor) whom are mostly individuals with little formal education, the survey questions were read and interpreted to about two third of the respondents, while those with good formal education filled the questionnaires on their own. In each case, research assistants with good education were recruited from within the local areas that were responsible for the tedious task of interpreting the questions to local language of the household respondent. The research assistants were trained to ask the questions (interpret from the local language to English) properly and in filling out the questionnaires for the households with little or no formal education. Methods used in identifying the survey participants were also clarified to them.

In addition, gender sensitive steps were taken to ensure representation of both males and females in the survey. This is because women play a significant role in water related issues particularly in developing countries (Shiva, 2002). Women, therefore, hold very vital information when it comes to water management issues in their homes and communities. Furthermore, men were also included because they hold key information on water supply and utilisation. Therefore, both male and female respondents were engaged.

Once respondents were identified, he or she is read the survey participant statement on the questionnaire as approved by Abertay University. The statement gave a brief description of the research, nature of participation and the confidentiality of participants.

4.3 Methods of Data Analysis

In this study, both parametric and non-parametric tests were employed in evaluating the quantitative and qualitative data. Generally, parametric tests are often used in the scientific study and are more robust than non-parametric tests. While in social sciences non parametric tests are the preferred choice. The following are the steps taken in analysing the data obtained for this study:

4.3.1 Thematic Analysis Procedure

Each manuscript was transcribed verbatim into a separately identified folder. The digitally recorded focus group discussions or individual interviews were re-played many times to ensure the adequate understanding of obtained data. As a standard digital recorder was used, it was possible to minimise the background noise and change the sound tones to maximise the clarity of voices.

The manuscripts were read through frequently, to become familiar with the overall picture of data (deductive analysis). That is; this approach was used to discern an overall and fundamental meaning of experiences (Hall, 2004). Then, line by line a search of manuscripts was undertaken to scan central themes (e.g. environmental problems, sustainable options, etc.). This included repeated ideas or statements “that say something” (Brunard, 1991). This process was accompanied by making notes about each manuscript.

Once again, the manuscript was re-read to check for common themes in the manuscripts. Indeed, so doing allowed the current author to become immersed in the data and thus the “life world” of participants (Gillis and Jackson, 2002). Once the author has become aware of the main issues found, as many headings as necessary were highlighted, then irrelevant materials which are referred to as “dross” (Brunard, 1991) were identified and excluded from the analysis (e.g. talking in a detailed way about the ownership sources of water supply).

Once the main themes were highlighted, a category system was created for each manuscript (e.g. Category One: all themes about issues related to environmental problems). Initially, as many categories as possible were generated, and materials of relevance were linked accordingly. Then the number of categories was reduced (collapsing stage) i.e. some of the ones that have similar contents (Brunard, 1991). Once the final version of categories was finalised, each of them was examined within the context of each question reported in the interview schedule.

As qualitative analysis is an on-going and dynamic process, during the writing up phase, if there is some doubt about certain findings, the current author checks the manuscript to ensure the credibility of analysis.

4.3.2 Axial Coding

Axial coding is a process of relating categories to their subcategories in qualitative data analysis (Strauss and Corbin, 1997). This data analysis technique is normally preceded by open coding, where the raw interview data or field notes are reduced into many ideas and concepts. They are identified and labelled accordingly, which sets the stage for axial coding.

In axial coding the data are regrouped so that the researcher may identify existing relationships more quickly. In this respect, the issues of groundwater management

are categorised based on the selected themes to represent the various opinions of the stakeholders in the different interviews and focus group discussions. This has allowed the exploration of all the different views and opinions of the stakeholders in a tabular form. Much detailed description of the axial coding methodology can be obtained from (West and Zimmerman, 1987; McMahon, 1995; Glaser, 1995).

4.3.3 Statistical analysis methods

The study has adopted the following statistical analyses:

4.3.3.1 General Linear Model (ANOVA)

This study fits the General linear model (GLM) for univariate responses of the Hydrochemical data obtained (Appendix B). In matrix form, this model is $Y = XB + E$, where Y is the response vector, X contains the predictors, B contains the concentration of ions to be estimated, and E represents errors assumed to be normally distributed with mean vector 0 and variance Σ . By means of the general linear model, the study performed a univariate analysis of variance and examines the differences among means of the concentration of cations and anions in the various boreholes using multiple comparisons.

In this regard, statistical test was carried out on the groundwater samples collected. The samples were tested for determining the differences in concentration of cations and anions across the different boreholes using analysis of variance (ANOVA); using

Tukey method in Minitab™16 statistical software (MINITAB®, USA). Means of ions that do not share the same superscript letter (a to j) within a row are significantly different ($p < 0.05$), based on grouping information of Tukey method at 95% simultaneous confidence interval.

Also, IBM SPSS statistical software (version 22) package was used in analysing the household survey data. The analysis of the collected household data was carried out (95% Confidence Interval) by the use of distributions tables of frequency counts, and employing of chi-square test on each of the hypothesis statements. Furthermore, descriptive statistics such as the mean, median, cross-tabulation, and frequencies were employed to analyse the socio-demographic characteristics of the respondents as well as to explain the overall perception of the respondents in relation to each of the variables tested.

4.3.3.2 Hypothesis testing of household survey data

In this study, inferential statistical tests (hypothesis test) were employed to test the relationship between the various environmentally related variables, the relationships between some selected socio-demographic variables and the environmentally related variables. From a statistical viewpoint, the null hypothesis provides actual numerical values so that the sampling distributions of inferential statistics are calculated. Hypothesis testing was used in this study to accept or reject the formulated hypotheses and determine that there is evidence or lack of evidence for

the various hypotheses formulated in the household survey data. Logically the null hypothesis denoted as H_0 and the alternative hypothesis is denoted as H_a .

The following hypotheses were formulated and tested in the study (chapter 5; section 5.4):

Hypothesis1:

H_0 : There is no relationship between Income of households and Willingness to pay for extra services.

H_a : There is relationship between Income of households and Willingness to pay for extra services.

Hypothesis 2:

H_0 : There is no relationship between Education status and Awareness on ground water contamination.

H_a : There is relationship between Education status and Awareness on ground water contamination.

Hypothesis 3:

H_0 : There is no relationship between Education status and Awareness on implications of dumping.

H_a : There is relationship between Education status and Awareness on implications of dumping.

4.3.3.3 Test-statistic and p Values Approach

In this study the critical value approach was used to carry out the descriptive statistical analysis. In this respect, the t test was carried out in the study to determine the means of the socio-demographic variables and the environmentally related variables. This approach sets up the hypothesis in terms of a test statistic which from a theoretical distribution is not directly observed. The p value is established to determine the probability of randomly selecting a test statistic that is equal or greater than the absolute value of the observed statistic or less than minus the absolute value of the test statistic (Benjamini and Hochberg, 1995). This approach is valid and is commonly used by all statistical packages. The following steps as outlined by Simes (1986) Benjamini and Daniel (2001) are followed in the hypothesis testing adopted by this study.

- I. State the null hypothesis (H_0) and the alternative hypothesis (H_A).
- II. Establish whether the test is one-tailed or two-tailed.
- III. Establish the probability of a false positive finding (i.e. α level).
- IV. Establish the sample size
- V. Calculate the observed descriptive statistic.
- VI. Find the most unlikely outcomes on the distribution around the observed statistic.
- VII. If the value of the statistic under the null hypothesis is not located within this interval, then reject then reject H_0 .

Lastly, contingency tables were created to summarise the observations on the categorical variables. For all the tables generated in the appendix section, the sole interest of the study largely lies in assessing whether or not there is any relationship or association between the socio-demographic variable and the environmentally related variable that constitute the table.

4.3.3.4 MODFLOW modelling

The chloride concentrations analysed in the water quality assessment was considered in the modelling. Chloride concentrations released from pit latrines into the underlying aquifers within the model domain (cell) are spread through the subsurface using a multi-species transport model, commonly referred to as MT3DMS (Zheng and Wang, 1999). The groundwater flow and mass transport modelling adopted in this study was carried out using MT3DMS codes to simulate chloride contamination due to impact of pit latrines. MODFLOW is used to determine the distribution of piezometric head and simulate groundwater flow. The model conceptualisation involves the following steps outlined in (Harabagh and McDonald, 1988):

- I. Defining a simulation domain and hydrogeological layers
- II. Dividing the model domain into different zones with distinct hydraulic properties
- III. Defining the model boundaries
- IV. Collecting and assigning hydraulic head values

The numerical code adopted by this study is the version of MODFLOW 2005 (version 1.18.01), developed by United States Geological Survey (USGS). Using the producer's protocol the program was activated in a typical serial processing mode. MODFLOW-2005 is a blocked-centred finite-difference FORTRAN based code, which has the capability of representing a complex three-dimensional groundwater flow system of a study area. MODFLOW-2005 has the capacity to simulate a wide range of geological and hydrogeological conditions under both steady and transient flow conditions, including interactions with the surface water regime (Zheng and Kinzelbach, 2000).

MODFLOW-2005 process solves a fundamental governing equation (see section 2.8.1.7) using a specified numerical method. The Groundwater Flow Process is further subdivided into smaller units called packages. Each package solves a specific hydrologic process, while the solver packages solve the linear simultaneous equations that are generated by the application of the governing equation. The Groundwater Transport Process solves the solute transport equation (Konikow et al. 1996).

The modular structure MT3DMS (Modular Transport Three Dimension Modelling Simulator) was used for simulating advection, dispersion/diffusion of chloride concentration within the modelled shallow aquifer of the Chad Basin around Maiduguri. The chemical reactions included in the model are equilibrium-controlled and first-order irreversible/ reversible kinetic reactions. MT3DMS is implemented with an optional, dual-domain formulation for modelling the mass transport of the chloride

in the groundwater. Detailed protocol and step-by-step methodological approach of the MODFLOW-2005, and MT3DMS can be found in (Harabaugh and McDonald, 1988; Zeng and Kinzelbach, 2000). These models are globally accepted and applied in areas of contaminant transport modelling and remediation assessment studies (McDonald and Harabaugh, 1988).

4.4 Methodology for developing the alternative guidelines

The alternative guideline for achieving sustainable groundwater management (see chapter 6; Tables 6.6 and 6.7) was developed by carrying out the following activities (steps I-VIII) below (Figure 4.11):

I. Formulation of the guidelines themes

Effective and efficient guideline development demands asking and answering key questions. Firstly, in developing a viable guideline for the study area, the researcher drafted key themes that are relevant to the objectives of the study. At this stage, questions such as why the alternative guidelines? Who will be responsible for their implementation and monitoring? What is the limit of their application? Were answered.

II. Scoping of the guideline and integrating study outcomes

Secondly, after answering the abovementioned questions, the researcher carried out scoping of the potential impact and benefits of the proposed guidelines to the local water users, policy makers, and other relevant stakeholder groups in the water and sanitation sector. Then the researcher developed closed ended questionnaires,

based on the existing problems of groundwater management in the case study area, and engaged the strategic stakeholders for their responses in providing solutions to these problems. The researcher considered the key outcomes of the study outlined in Figure 6.5 (see chapter 6 for details). All the responses of the stakeholders were accommodated in the proposed guideline at this stage.

III. Search of evidence

At the third stage, the researcher carried out extensive review of grey literatures from the World Bank, UNICEF and the UNDP to search for evidence of existing guidelines discussing similar situation. Next, the researcher carried out synthesis and comparison of the contents of existing frameworks with the recommendations outlined by the researcher to avoid duplication of functions.

IV. Formulation of guideline recommendations

After the search of evidence from the contents of existing frameworks in grey literatures, the author in collaboration with the strategic stakeholders (based on consensus) adopted the set of recommendations as a draft guideline.

V. Writing the guideline's draft version

Lastly, after adopting the recommendation, the researcher structured the contents of the recommendation and drafted the first draft version of the guidelines. Furthermore, the guidelines are written to accommodate any future recommendation as it evolves. It is comprehensive and flexible enough to allow adaptation to diverse

settings and circumstances of protecting vulnerable groundwater resources from the impact on-site sanitation systems in the study area.

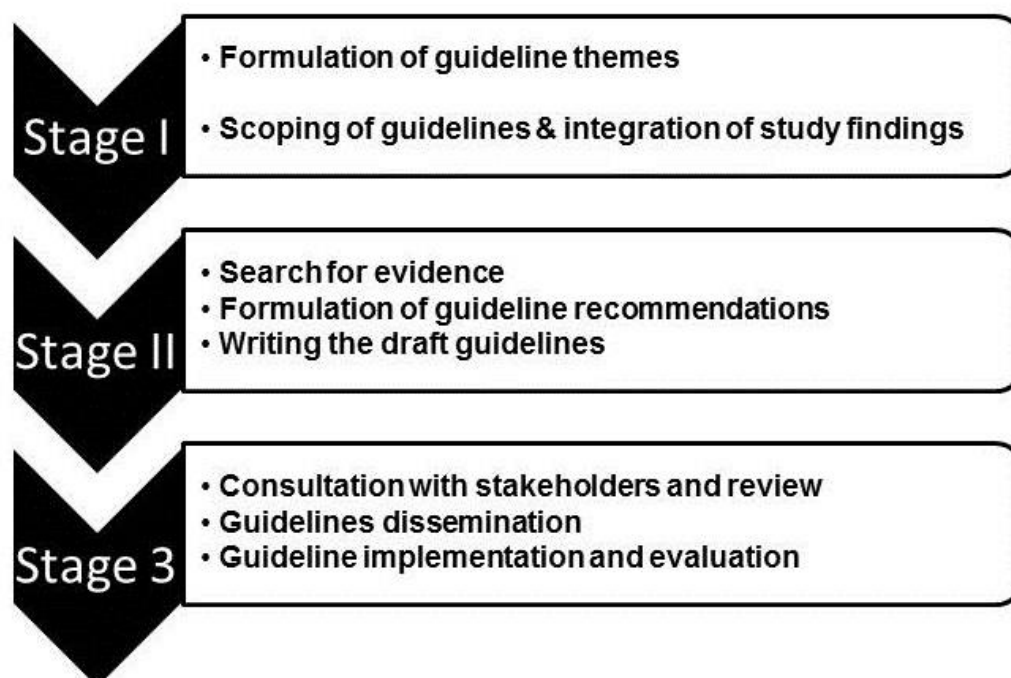


Figure 4.11 Guidelines development steps

VI. Consultation and review

The final stages of guideline development involve review by its users and approval by the stakeholders involved. Within this phase the adequacy of the guidelines were evaluated, particularly for its feasibility and applicability in the case study area.

Local community leaders, government officials and politicians are invited to review the draft. In addition, local residents and primary water users are encouraged to send their review comments strictly time-limited within six weeks. However, up to till this time no conflict of interest is expressed by any stakeholder in the water and sanitation sector.

VII. Guideline dissemination

Dissemination involves making guidelines accessible, advertising their availability, and distributing them widely. A range of dissemination strategies can be effective, but there is too little evidence to support decisions about which strategy is efficient under which circumstances. In general, the use of multi-faceted dissemination strategies is recommended. The a copy of the guideline published in the special publication series of the International Association of Hydrogeologists titled “Solving the groundwater challenges of the 21st century” (Vogwil, 2016). This is submitted to the Borno state Government for adoption. Also, the guidelines were interpreted to the local language (Kanuri) and presented to the primary water users in a local workshop in collaboration with the strategic stakeholders in the case study area.

VIII. Guideline implementation and evaluation

Guidelines do not implement themselves; local ownership of the implementation process is crucial for changing practice. The researcher is responsible for the development of the guidelines and their implementation is the responsibility of the local and state governments in the study area. At an appropriate time after guideline dissemination and implementation an evaluation is necessary for insight into its impact. Thus, future studies should focus on this aspect and improve on it.

4.5 Summary and conclusion

The chapter outlined that the case study methodology that utilises both quantitative and qualitative tools of data collection is the most appropriate methodology that can be adopted in achieving the overall aim of the study. In this respect, the overall aim of the study is to develop guidelines for the sustainable management of groundwater resources in sub-Saharan Africa region; therefore, the mixed method case study methodology provided a more detail insight of the phenomenon under investigation. In this case study, modelling will be employed to predict future contamination scenarios. Thus, the guidelines that will be developed is based on informed position. The new framework will be based on the output of the modelling and other secondary information will be used to compare standards.

The pragmatic approach employed by the study combined both positivism and interpretivist and this has demonstrated the robustness of the methodology in providing solutions to the persistent and perceived problem of groundwater contamination in the case study area. The quantitative analytical approaches of the study is not limited to any epistemological believe, while the qualitative methods including person-to-person semi-structured interviews, and focus group discussions are guided by interpretivist philosophical believes.

Overall, the combination of the social and technical dimensions of hydrogeology will bridge the gap that the study intends to address. Moreover, involving the local stakeholders in groundwater management will enable the implementation findings of

the study with limited effort. Most importantly, all the relevant stakeholders will benefit from the new framework. The next chapter presents the stakeholder engagement (social) and the hydrogeological (technical) aspects of the study.

CHAPTER 5

STAKEHOLDER ENGAGEMENT & HYDROGEOLOGICAL RESULTS

5. Introduction

This chapter presents results from the stakeholder engagement and hydrogeological analyses. Firstly, results obtained from the different methods of stakeholder engagement (interviews, focus group discussions, and household survey) are presented in section 5.1. Secondly, results obtained from the hydrogeological (groundwater quality and sediments sample) analyses are presented in section 5.1. Lastly, the chapter discusses the results from the social and hydrogeological dimensions. The synthesis from the discussions in this chapter and the output of modelling in chapter 6 informed the development of the alternative guidelines for sustainable groundwater management in chapter 7.

5.1 Results from the Strategic Stakeholders Engagement

Developing effective and sustainable groundwater management framework requires harmonisation of multiple stakeholders' responses including the strategic and primary stakeholders.

5.1.1 Opinions from the Semi-structured Interviews with the Strategic Stakeholders across the various Ministries and Organisations in Maiduguri

As outlined in previously (chapter 4) (Table 4.7), a total of twelve strategic stakeholders are interviewed in the case study area. Table 5.1 summarises the findings from the interviews:

Table 5.1 Opinions of the strategic stakeholders from (axial coding) the interviews

Themes	sub-themes	Properties (stakeholders opinion)
ENVIRONMENTAL PROBLEMS	Groundwater contamination	Likely to occur due to solid waste disposal in open dumpsites
		Due to domestic wastewater and pit latrines
		Contamination can occur due to multiple activities
	Knowledge about contamination	Stakeholder is fully knowledgeable about contamination issues
		Stakeholder is fairly knowledgeable
		Stakeholder is totally not knowledgeable about contamination issues
	Concerns about contamination	Stakeholder is extremely concerned about contamination
		Stakeholder is reasonably concerned about contamination
		Stakeholder is totally unconcerned about contamination

What follows is the detailed presentation of the results (Table 5.1) above:

5.1.1.1 Groundwater Contamination

The problem of groundwater contamination can be attributed to a multitude of sources across the metropolis; open dumpsites, pit latrines, and other sources. The severity of these sources, according to the stakeholders interviewed, varies from place to place in the city. Consequently, the entirety of the local residents utilise pit latrines due to its affordability and traditional attachment to the people in the case study area.

Also, most government officials and the academia attribute the use of fertiliser and organic manure as a potential source of groundwater contamination. Also, the proliferation of petrol stations and the concentration of cottage industries such as tanneries and dying works can also constitute a significant threat to the shallow groundwater system.

5.1.1.2 Knowledge about Groundwater Contamination

The officials from the ministries of water, environment, and health, and those from the academia were more knowledgeable about the issues related to groundwater contamination. This acquaintance was due to their professional experience or the relevance of their respective ministries in relation to management of water resources.

Also, some interviewees from other agencies and organisations such as the urban development board, the metropolitan council, women forum, and an NGO the Sahel green belt were fairly knowledgeable about the status quo; however, at present the groundwater quality is good. However, this group of stakeholders stressed the importance of the availability of real time groundwater data/ information for the various stakeholder groups and organisations. From the foregoing, it can be claimed that knowledge about groundwater contamination issues is very good among the strategic stakeholders interviewed. Despite their knowledge, some of institutional stakeholders, except for handful in the academia, they are not familiar with groundwater modelling tools including their application.

5.1.1.3 Concerns about Groundwater Contamination

Despite the disparity of knowledge among the stakeholders interviewed, concerns about groundwater contamination were very high (Figure 5.1). Majority of the interviewees were worried that contaminated water can be harmful to human life, and they attest that they are willing to be involved in addressing the situation. However, despite their concern, an interviewee confirmed that there is no cause for alarm at present, but warned that people should avoid unwholesome environmental attitude towards waste disposal.

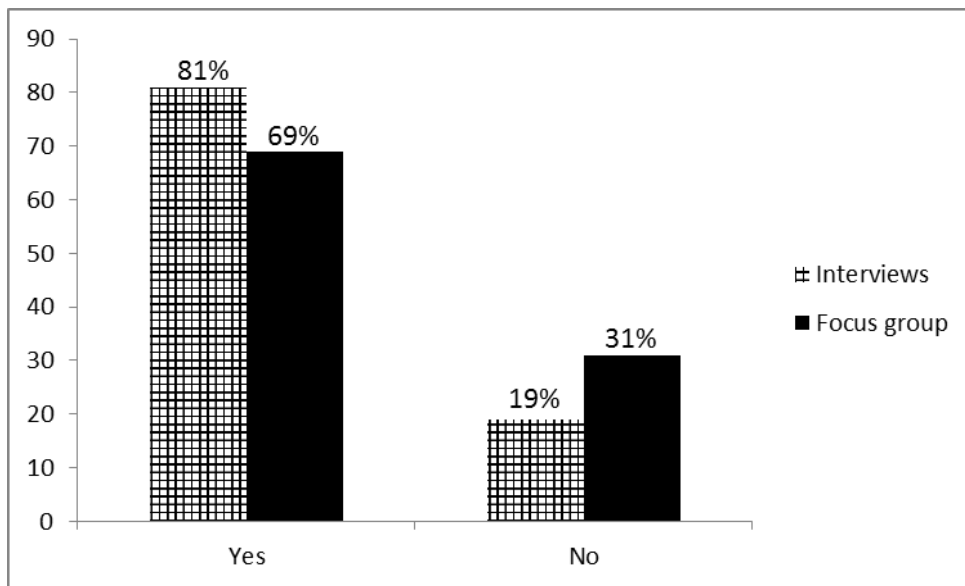


Figure 5.1 Stakeholder concerns about groundwater contamination

Noteworthy at present, none of the stakeholders interviewed was affected by the problems of contamination. Interviewees from the academia and the ministries responsible for water supply and healthcare service delivery were the extremely concerned; while those representing individual groups were the least concerned about the issue.

5.2 Stakeholders opinion from the various Focus Group Discussions

The results of the six focus group discussions (three each from the two sites) as carried out by the study are presented in Tables 5.2 and 5.3. The result suggests that the opinions of the primary stakeholders are vital for the development of a sustainable framework in managing groundwater resources in the case study area.

Table 5.2 Opinions from the axial coding of the 3 focus groups workshops in site 1

Themes	Sub-themes	Focus group 1	Focus group 2	Focus group 3
ENVIRONMENTAL PROBLEMS	Knowledge about contamination	Participants are knowledgeable	Participants felt they are affected	Participants are familiar
		Participants are not knowledgeable	Participants felt they are not affected	Participants are not familiar
	Concerns about contamination	Participants are concerned	Participants are worried about it	Participants are concerned
		Participants are not concerned	Participants are not worried	Participants are not worried about it
	Common causes of contamination	Dump sites	Waste disposal	Pit latrines
		Pit latrines	Human and animal wastes	Local tanneries
		Not sure	Domestic waste water	Dumpsites
	Wastes generated	Residential waste	Domestic wastes	Commercial wastes
		Commercial wastes	Agricultural wastes	Domestic wastes
		Both	Commercial wastes	Agricultural activities
	Waste disposal	Open dumping	Dumping in pits	Dumping in old wells
		Dumping in river and gullies	Dumping on land	Burning wastes
		Burning	Dumping in bush	Dumping in drainages

What follows is the detailed presentation of the results shown in table 5.2:

5.2.1 Knowledge about Groundwater Contamination

The participants of the three focus groups in site 1 show similarity in their opinion, except on a few instances. Majority of the participants are not familiar with the issues

attributed to groundwater contamination. Whilst it was acknowledged that awareness creation is needed at the community level. Few issues might be pointed out; participants are knowledgeable about surface water contamination, the non-visible nature of groundwater is a critical factor in participants' decisions, and participants like the local farmers failed to recognise the impact of their activities on groundwater resources, and they could not classify well water as groundwater. Thus, specific awareness creation programmes will increase the capacities of the focus group participants.

5.2.2 Concerns about Groundwater Contamination

Similarly, concerns about groundwater contamination are extremely low among the participants. This can be connected with the lack of knowledge about contamination issues as stated above. However, some participants were wary of this problem and felt that it is a major issue to contend with. Taking these opinions into consideration, the contrasting views as expressed by the participants can be credited to their differences in interpersonal reasoning and the insensitivity towards environmental issues.

5.2.3 Common Causes of Groundwater Contamination

Participants of the focus groups opined that dumpsites, pit latrines, tanneries and domestic wastewater are the major causes of contamination in their areas. However this view is not shared by all but, majority attest that these are the most significant.

Arguably, participant's thoughts were influenced by education and the mass media. Most critically, the cultural attitudes of the participants are a determining factor to consider. However, it is worthy to note that people's attitudes can only be influenced but cannot be changed in this regard.

5.2.4 Waste Generation

Most participants of the three focus groups in Moduganari area are of the view that the most commonly generated wastes in their areas are domestic in nature; food wastes, woods, ash, dust and stones. Some participants expressed that organic and paper wastes are generated in high amount from the local market areas of their communities. Hence, it can be reasoned that the wastes generated in these areas are mainly domestic wastes from homes and commercial wastes from local businesses. Debatably, the uniformity in composition of the wastes produced across the area suggests that all the participants belong to the same socio-economic category (the less affluent).

5.2.5 Waste Disposal

Waste disposal methods across the area include; open dumping on land, dumping in river and gullies, dumping in pit, and open burning. Notably, the disposal of wastes in open space in these areas suggests that adequate sanitation facilities are lacking.

Table 5.3 Opinions from the axial coding of the 3 focus groups workshops in site 2

Themes	Sub-themes	Focus group 4	Focus group 5	Focus group 6
ENVIRONMENTAL PROBLEMS	Knowledge about contamination	Participants are not conversant	Participants felt they are affected	Participants are acquainted
		Participants are conversant	Participants felt they are not affected	Participants are not acquainted
	Concerns about contamination	Participants are worried	Participants are bothered about it	Participants are anxious
		Participants are not worried	Participants are not bothered	Participants are not anxious about it
	Common causes of contamination	Pit latrines	Human and animal wastes	Pit latrines
		Dump sites	Waste disposal	Dumpsites
		Not sure	Domestic waste water	
	Wastes generated	Commercial wastes	Domestic wastes	Commercial wastes
		Residential waste	Commercial wastes	Domestic wastes
		Both	Agricultural wastes	Agricultural activities
	Waste disposal	Burning	Dumping in pits	Dumping in old well
		Open dumping	Dumping on land	Dumping in drainages
		Dumping in river and gullies		

5.3 Environmental Problems

As shown in table 5.3 environmental problems are divided into five sub-themes; knowledge about contamination, concerns about contamination, common causes of contamination, waste generation, and waste disposal.

5.3.1 Knowledge about Groundwater Contamination

The participants of focus groups 4, 5 and 6 in Gwange area expressed contrasting views; some of the participants are familiar with the issues attributed to groundwater contamination while did not. Since it is very likely that people with experience and elementary education are familiar with contamination problems, it is obvious that those participants without knowledge are the less educated or inexperienced. In order to explore the thinking behind how groundwater contamination occurs, unconvincing layman explanations were made by those knowledgeable participants' especially the older ones, the more youthful participants failed to provide resounding ideas.

5.3.2 Concerns about Groundwater Contamination

Equally, concerns about groundwater contamination are exceptionally little among the participants of the three focus groups in Gwange area. This cannot be unrelated to the lack of acquaintance about contamination issues as evidenced above. Yet,

some participants were worried about this problem and assume that it is a key issue to deal with.

Considering these views, the conflicting beliefs as expressed by the participants can be credited to insensitivity towards environmental problems, in this regard, it can be claimed that the water consumed by the focus group participants in Gwange area is safe for drinking; they were only unhappy with the current erratic nature of the water supply situation.

5.3.3 Common Causes of Groundwater Contamination

Participants of the focus groups in Gwange opined that pit latrines, dumpsites, and domestic wastewater are the major causes of contamination in their areas. Possibly, the most common causes of groundwater contamination in the area are pit latrines and dump sites where solid and organic wastes are dumped. The proliferation of dumpsites can be attributed to the non-existence of waste disposal facilities and the very old tradition of disposing waste in the open.

5.3.4 Waste Generation

Participants of the three focus groups in Gwange area are of the opinion that the most common wastes generated in the area constitute both domestic and commercial wastes; variety of food wastes, rags, polythene bags, wastes from butchery, barbers and mechanics, etc. From this evidence, it can be contended that

the wastes generated in these areas are compositionally the same. Possibly, the composition indicates that the participants belong to the low ranking group of citizens as it does not contain an element of luxury packages.

5.3.5 Waste Disposal

Waste disposal ways across the area is mostly through open dumping on land, dumping in gullies and rivers, and open burning. Remarkably, it can be rational to say the people are lack facilities for the disposal of their wastes. Thereby, compelling them to dispose of their wastes in all space they find.

5.4 Socio-demographic characteristics of the households surveyed in the study area

5.4.1 Sex of Respondents

A total of 288 respondents were surveyed in the two study sites. About 63.5% were male while the remaining 36.5% were females (Table 5.4).

5.4.2 Marital Status

There are four marital characteristics among the respondents in the study area; these are the singles, the married, the divorced and the widowed. About 22.9% of all the respondents were yet to get married, while about 43.1% were married. 16.3% were divorced or separated, and the remaining 17.7% were widowed

5.4.3 Age of the Respondents

The highest frequencies of the heads of the households surveyed are above 40 years of age. The result consistently shows that the highest proportion (41%) of the respondents fall in the age group of 41 and above. Likewise, the age group 18-25 constitutes 10.4% of the sample, those between the age group of 26-33 make up 22.2%, and those in the range of 34-41 constitutes about 26.4%.

5.4.4 Educational attainment of the respondents

The highest educational attainments (47.2%) in the study area are those that attended primary school. More than 23% of the respondents have been to secondary school. The graduates constitute 12.8%; this category includes graduates from the University, Polytechnics, and Colleges of Education. Other important categories of respondents in the study area are those that have attained Quranic/Arabic education. This category constitutes the remaining 16.7% of the surveyed population.

5.4.5 Income of the households surveyed

The result of the survey show that close to two-third of the total number of respondents earn less than N100, 000 annually (USD 650/year). In the same area, 29.9% of the respondents earn between N100, 000-N500, 000 (USD 650-3, 250/year). Another category that exists (10.1%) is those earning between N500, 000-N1Million (USD 3,250-6,311.14/year).

5.4.6 Employment status of Respondents

The uneven distribution of respondents among the various employment statuses in the study area show that there are more self-employed (42.4%) individuals; as traders (market men and women), farmers, local crafts men and women, mechanics and artisans than any other group. Those in the category of students constitute

about 11.5%. Individuals employed by the three tiers of government (Federal, State, and local) as civil servants, most of whom were junior to mid ranking officers constitute about 37.5%, and those working in the private sector make up the remaining 8.7%.

5.4.7 Household size

In the study area, households with at least 5 inhabitants constitute 36%, those in the range of 6-11 constitute 25.7%, and the remaining percentage is dominated by those with more than 11 inhabitants per household.

Table 5.4 Summary of socio-Economic characteristics of the households surveyed

Location/ Socioeconomic characteristics	Site 1		Site 2		Sum Total	
	No	%	No	%	No	%
Sex						
Male	99	62.7	84	64.6	183	63.5
Female	59	37.3	46	35.4	105	36.5
Total	158	100	130	100	288	100
Marital status						
Single	34	21.5	32	24.6	66	22.9
Married	67	42.4	57	43.8	124	43.1
Divorced	25	15.8	22	16.9	47	16.3
Widowed	32	20.3	19	14.6	51	17.7
Total	158	100	130	100	288	100
Age						
18-25	14	8.9	16	12.3	30	10.4
26-33	41	25.9	23	17.7	64	22.2
34-41	50	31.6	26	20.0	76	26.4
41 and above	53	33.5	65	50.0	118	41.0
Total	158	100	130	100	288	100
Education						
Graduate	10	6.3	27	20.8	37	12.8
Secondary	42	26.6	25	19.2	67	23.2
Primary	70	44.3	66	50.8	136	47.2
Other	36	22.8	12	9.2	48	16.7
Total	158	100	130	100	288	100
Household income						
>N100, 000	78	49.4	95	73.1	173	60.1
N100,000-N500, 000	54	34.2	32	24.6	86	29.9
N501,000-N1 Million	26	16.5	3	2.3	29	10.1
<N1 Million	0	0	0	0	0	0
Total	158	100	130	100	288	100
Employment status						
Student	13	8.2	20	15.4	33	11.5
Self-employed	66	41.8	56	43.1	122	42.4
Govt. employee	68	43.0	40	30.8	108	37.5
Private sector	11	7.0	14	10.8	25	8.7
Total	158	100	130	100	288	100
Household size						
0-5	58	36.7	48	36.9	106	36.8
6-10	30	19.0	44	33.8	74	25.7
11-15	52	32.9	25	19.2	77	26.7
<16	18	11.4	13	10.0	31	10.8
Total	158	100	130	100	288	100

5.4.8 Common causes of groundwater contamination

The survey results for the two sites show that pit latrines and septic tanks are having the highest frequency score (53.1%). In both locations open dumpsite and other sources ranked next to pit latrines with 28.5 and 38.5% respectively. Correspondingly, pit latrines are the most commonly used on-site sanitation facility, over 90% of the households surveyed utilise this system because of its traditional attachment and affordability.

5.4.9 Wastes generation and collection

The wastes generated in the study area are mainly domestic wastes from residential areas and commercial wastes from local businesses and markets. These categories of wastes include organic and solid wastes. In the two sites, majority (60.4%) of wastes generated are domestic in origin while the remaining 39.6% are from commercial activities. Singularly, in site 1, about 52.5% of the wastes generated are from residential areas while 47.5% are commercial in nature. The distribution is also similar in Site 2 where 70% of the total wastes generated are domestic and the remaining (30%) are from commercial activities.

The result of this survey further indicates that 93.4% of the respondents attest that formal waste collection systems are totally non-existent in both areas. The remaining few percentages (6.6%) are of the opinion that some method of local waste disposal system in the form of pits are in place at various locations as local dumpsites.

5.4.10 Waste disposal method

The commonest methods of waste disposal in the study area as shown in (Figure 5.2) include open dumping on land (48.3%), dumping in drainages (16.7%), and communal bin (5.6%). Other mode of disposal (29.5%) includes burial, burning and the use of old wells. An attempt was made to test statistically the level of association of the pattern of waste disposal in the two sites of the study area. The result of the test indicate that the pattern of waste distribution in the two sites are not significantly different ($p\text{-value} < 0.001$).

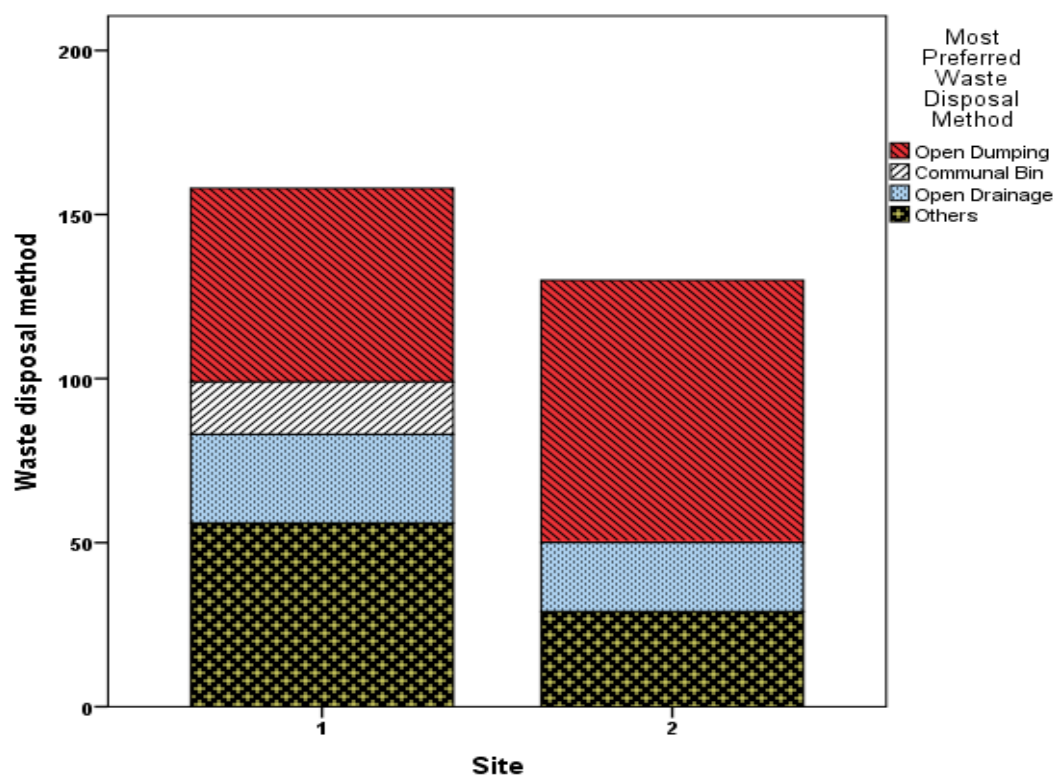


Figure 5.2 most preferred waste disposal methods

5.4.11 Willingness to pay for improved sanitation services

Results of the survey showed that 61.8% of the respondents are not willing to pay for any amount in exchange of improved services. This is because the respondents view this as the responsibility of the various governments (federal, state and local); the remaining (39.2%) believed that local communities can equally contribute as a major stakeholder and a beneficiary. Also, the households were asked on how much they are willing to pay, slightly over 29% are willing to pay N2000 (USD 9.09) annually. Also, most of the respondent attest that with good jobs and economic independence, they will pay even higher than what is obtainable currently. In this regard, statistical test was carried out to determine if relationship exists between household income and willingness to pay.

Hypothesis 1:

H_0 : *There is no relationship between Income of households and Willingness to pay for extra services.*

H_1 : *There is relationship between Income of households and Willingness to pay for extra services.*

Table 5.5 Summary of test statistics for household income and willingness to pay

Chi-Square Tests			Asymp. Sig. (2-sided)
	Value	Df	
Pearson Chi-Square	10.051 ^a	3	.007
Likelihood Ratio	9.010	3	.012
Linear-by-Linear Association	3.457	1	.033
No of Valid Cases	288		

Our probability of type 1 error (α) is set to a standard value of 0.05 Test statistics: $\chi^2_{\text{Cal}} = 10.048$ with P-value = 0.006

Taking the test statistics (Table 5.5) into consideration, at P-Value = 0.006 < 0.05 we reject the null hypothesis and accept the alternative hypothesis. Hence, we conclude

that, relationship exists between household income and willingness to pay for extra sanitation services by respondents.

5.4.12 Household's awareness level on groundwater contamination

The sum total of the household survey shows that more than 87% of the respondents are unaware of any issue related to groundwater contamination, only about 12.15% of the households are aware of groundwater contamination issues as shown in Figure 5.3. The result further showed that out of those that are aware, almost half of the population assume that the level of groundwater contamination is low, another 34.3% assume that the level of contamination is moderate, and lastly the remaining 17.1% could not specifically disclose the level of contamination.

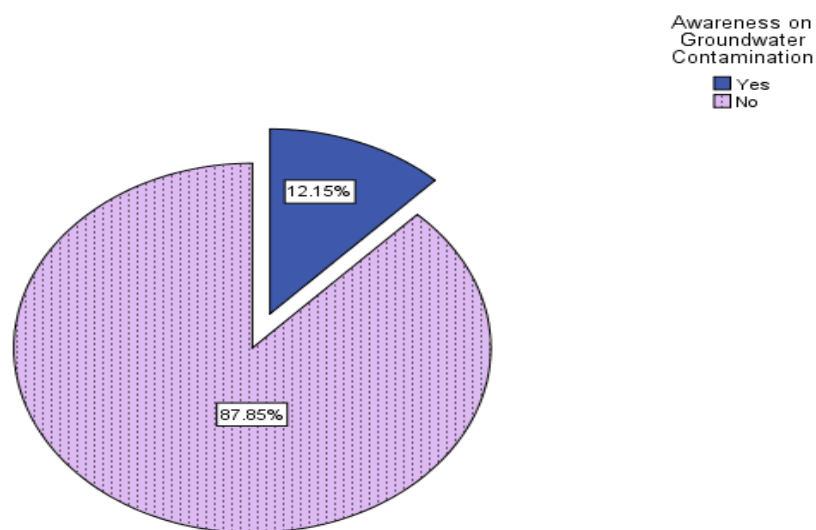


Figure 5.3 Households awareness about groundwater contamination in the study area

5.4.13 Distribution of Awareness about the implications of dumping waste by sex and educational level

Descriptive statistical analysis was carried to investigate the level of awareness of the various households surveyed on the implications of incessant waste dumping in the open space (by sex and educational status of the respondents). In this respect, only a handful of (n=50) households were aware of the implications of incessant waste disposal. A majority of the households (n=238) households were totally unaware or ignorant of the implication of dumping wastes incessantly.

Also, the analysis shows that no participant with secondary school qualification is aware of the implications of dumping wastes in the open space. Likewise, 33 out of about 50 participants (29 males and 4 females) with primary school qualification are aware of the consequences of dumping wastes in the open space. In general, about 40 out of 143 male respondents are aware of the effects of uncontrolled waste disposal while the remaining 103 male participants are unaware; likewise only 10 out 95 female participants are aware of the effects of dumping wastes in the open space.

In testing for the statistical relationship between the educational attainment or status of respondents and their awareness about groundwater contamination; a hypothesis testing was carried out.

Hypothesis 2:

H_0 : There is no relationship between Education status and Awareness on ground water contamination.

H_1 : There is relationship between Education status and Awareness on ground water contamination

Table 5.6 Summary of test statistics for level of education and awareness level

Chi-Square Tests			Asymp. Sig. (2-sided)
	Value	df	
Pearson Chi-Square	12.059 ^a	3	.007
Likelihood Ratio	11.007	3	.012
Linear-by-Linear Association	4.568	1	.033
No of Valid Cases	288		

Our probability of type 1 error (α) is set to a standard value of 0.05 Test statistics: $\chi^2_{\text{Cal}} = 12.059$ with P-value = 0.007

Considering the table 5.6 above, at P-Value = $0.007 < 0.05$ we reject the null hypothesis and accept the alternative hypothesis. Thus, we conclude that, there exists relationship between awareness about groundwater contamination and the education status of the respondents.

Furthermore, a statistical test was carried out to ascertain the relationship that exists between the respondent's level of education and their awareness about the implications or effects of incessant waste disposal in the open space.

Hypothesis 3:

H_0 : There is no relationship between Education status and Awareness on implications of dumping.

H_1 : There is relationship between Education status and Awareness on implications of dumping.

Table 5.7 summary of test statistics for education status and awareness about dumping

Chi-Square Tests			Asymp. Sig. (2-sided)
	Value	Df	
Pearson Chi-Square	28.226 ^a	3	.000
Likelihood Ratio	32.949	3	.000
Linear-by-Linear Association	5.815	1	.016
No of Valid Cases	288		

Our probability of type 1 error (α) is set to a standard value of 0.05, Test statistics: $\chi^2_{\text{Cal}} = 28.226$,

The test of the statistics as indicated above (Table 5.7) shows that at P-Value = $0.000 < 0.05$ we reject null hypothesis and accept the alternative hypothesis. Thus, we determine that, there exist relationship between level of education of respondents and their awareness on the implication of dumping of waste.

5.4.14 Distribution of population growth concerns and urban growth concerns by age

The descriptive statistical analysis show that about 50% of the respondents of the age group 18-25 were concerned with the effect of population growth in the study area. In this category, 9 out of the 30 respondents were also concerned with likely impact of uncontrolled urbanisation. Also, about 30 out of 64 respondents that are within the age group of 26-33 are concerned with the impact of population growth; about 14 of them were also concerned about urban growth. Furthermore, 32 out of

76 respondents of the age group 34-41 are also concerned with uncontrolled population growth in the study area, 14 respondents in this same category were also concerned about uncontrolled urbanisation in the study area. Lastly, 45 out of 118 respondents of those in the age group of 41-above were seriously concerned about the likely impact population growth will have on the groundwater resources of the study area. Only 19 respondents in this category are concerned about the likely impact of urban growth on the groundwater aquifers.

5.4.15 Distribution of population growth concerns and urban growth concerns by educational level

In furtherance to the concerns about the impact of population growth and uncontrolled urbanisation on the groundwater aquifers of the study area, the statistical analysis further investigates the relationship of the concerns with educational level of the respondents. In this respect, the analysis shows that only 56 out of 136 respondents that had primary school certificate are concerned with population growth. About 27 out of the 56 respondents are also concerned with the likely effect of uncontrolled urban growth on groundwater resources. Also, about 29 out of the 57 respondents with secondary school level qualification are concerned with population growth; about half of the 29 respondents are equally concerned with the impact of urban growth on the groundwater resources.

Furthermore, 17 out of 37 respondents whom are university, polytechnic, and college graduates were concerned with the effect of population growth on the groundwater aquifers, only a handful of the graduates were concerned with the effect of

uncontrolled urbanisation on groundwater resources of the study area. Lastly, about 20 out of 48 respondents with other qualifications are concerned with the impact of population growth on the groundwater resource, while 8 of these 20 respondents are concerned with the likely effect of urban growth on the groundwater of the study area.

5.4.16 Sustainable options for achieving sustainable groundwater management

In achieving a sustainable system, the respondents were asked to choose from a range of options on how sustainable groundwater management can be achieved. Divergent views and opinions were expressed as shown in Figure 5.4. Some (40%) of the households were of the opinion that both government and private investment in the water and sanitation sector is needed, while 33% opined that strict legislations is the best way of addressing the problem. About 17% of the respondents are of the opinion that community participation is the best strategy for addressing the current problem. Lastly, 10% of the households view controlling of wastes from source as the best alternative.

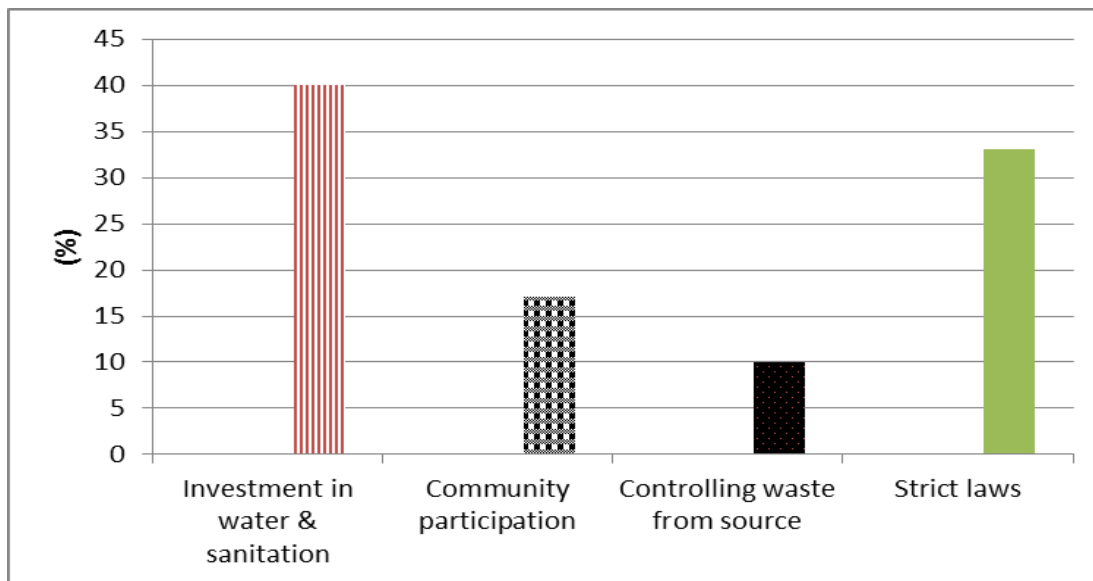


Figure 5.4 Households views on ways of achieving sustainable groundwater management

5.5. Hydrogeological Dimension

This sub-section presents the results from the hydrogeological investigations carried out in the study.

5.5.1 Site Description for Hydrogeological Assessment

In relation to the sources of contamination, the potential sites selected to carry out the sampling all fall within the Gwange and Moduganari areas of the metropolis. These are the areas with the highest anthropogenic impacts due to highest population densities, poor sanitation systems, and the ever increasing urban informal settlements. The borehole selection criteria and sampling strategy outlined in the methodology chapter was used to identify the potential sites for carrying out the hydrogeological assessment in relation the contamination sources. The boreholes

selected are all within 100 meters vertical interval from potential contamination sources. Also, the full details of the physico-chemical parameters of interest as well as the overall hydrogeological methodologies employed in the study are provided in the methodology chapter.

5.5.2 Pollution Pathways in Maiduguri

The potential pathways in the study area taken by these contaminants to travel is through the pore spaces of the sediments and fractures that exists in the sedimentary formations of the area; the contaminants move downward through this medium and infiltrate into the unsaturated zone and then to the saturated zone. A borehole strip log of selected boreholes constructed by this study for Moduganari and Gwange areas revealed that the Chad formation is constituted of sand, coarse sand (gravel), silt, and interbedded clay layers (Figure 5.5).

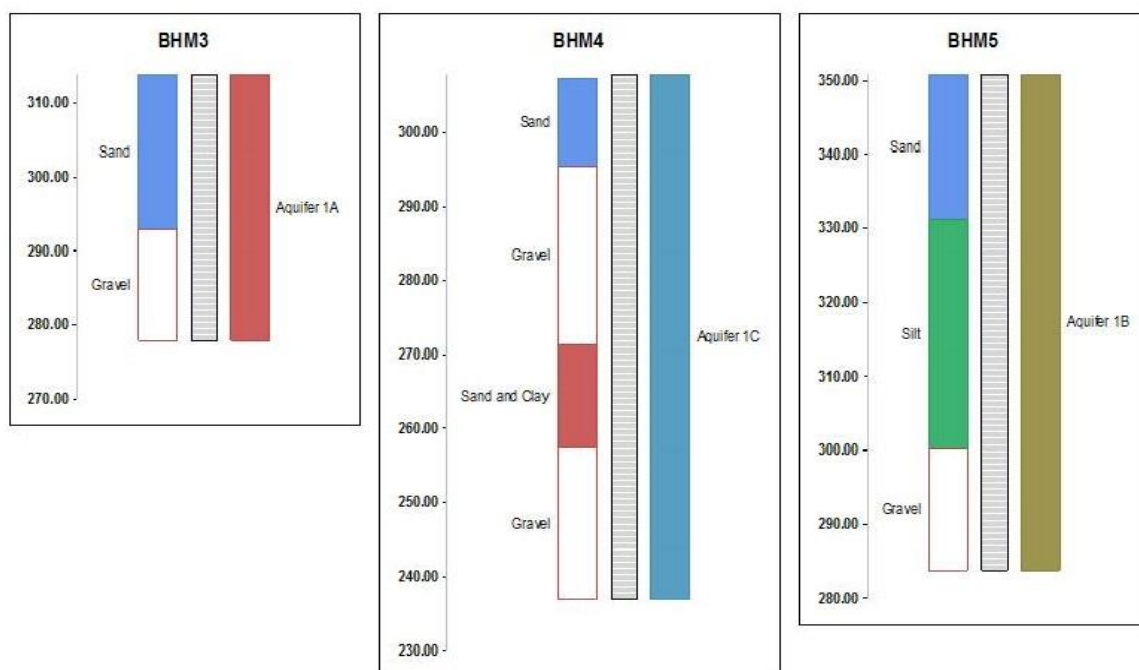


Figure 5.5 Strip logs of selected boreholes in Moduganari area showing the local geology and aquifer

An investigation of the uppermost sandstone unit in Moduganari area reveals that the sandstone layer is close to 20 meters as shown (Figure 5.5) above. This layer is wholly composed of coarse sand (1mm) and medium sand (500 μ m) particles constituting about 24.4% and 17.9% of the total sediment sample respectively. This layer is also characterised by fine gravel (2mm) with about 15.8 weight percentage. Other components of this sandstone layer include fine sand (150 μ m) and coarse silt (63 μ m) representing about 5.62% and 4.4% of the total weight percentage (Tables 5.8. and 5.9). The distribution of the grain morphology showed that 31% of the sandstone samples have very angular grains; about 17% of the samples have angular grains. Also, another 17% of the samples have sub-angular grains, 22% with sub-rounded grain shapes, and lastly 11% of the total samples have rounded grains (Figure 5.6).

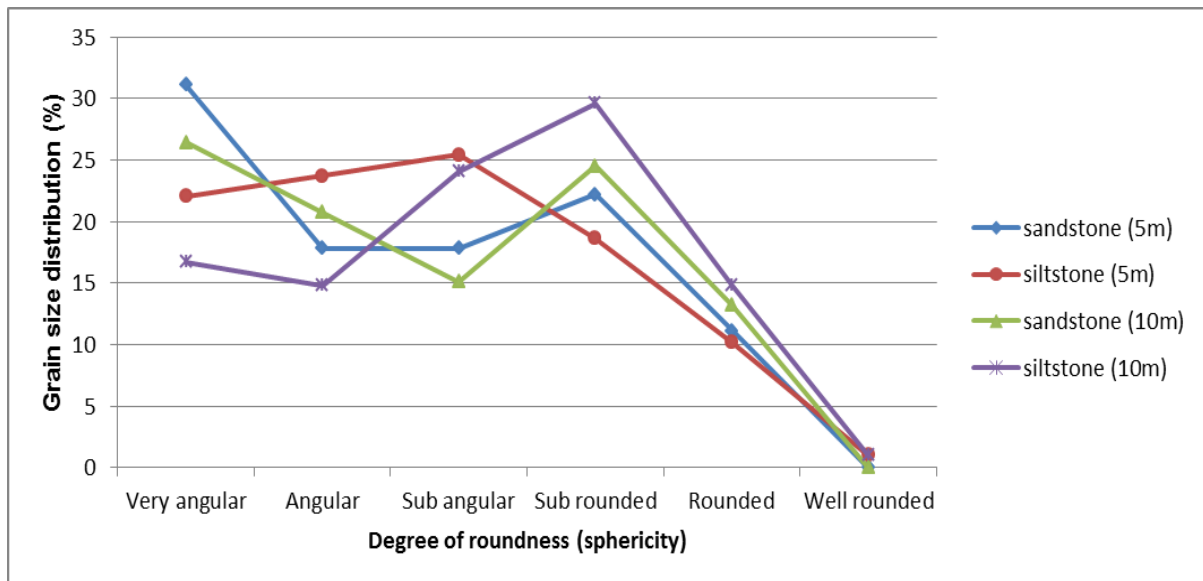


Figure 5.6 Grain Morphology analyses for Moduganari area (site 1)

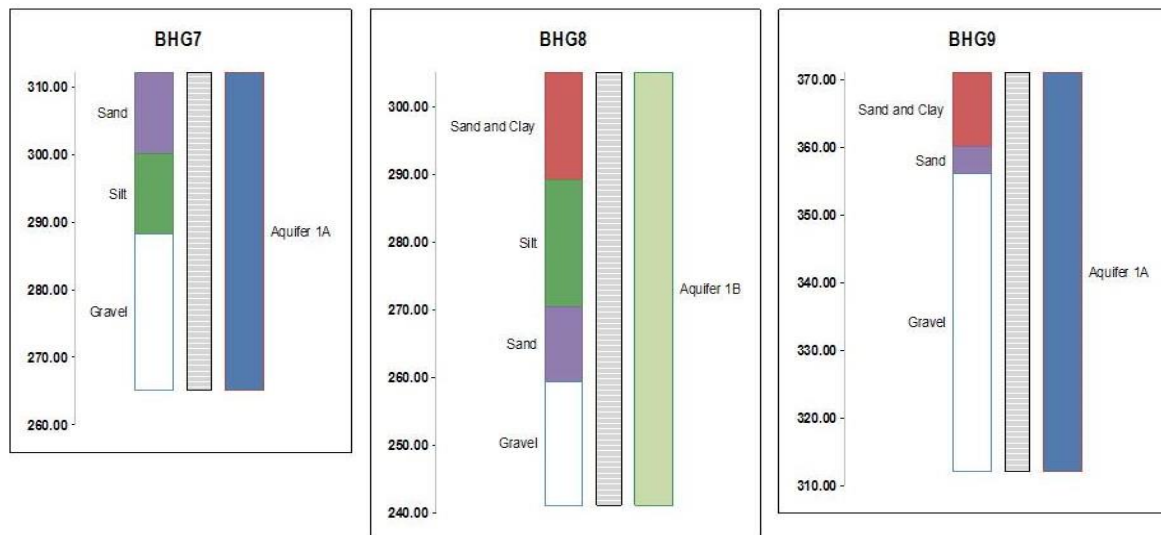


Figure 5.7 Strip logs of selected boreholes in Gwange area showing the local geology and aquifer

Similarly in Gwange area, the uppermost layer is made up of the mixture of sandstone and clay. The layer is about 10 metres thick (Figure 5.7), the samples obtained for this layer show that it is principally composed of fine gravel (2mm) constituting about 13.63% of the sample. Coarse sand with varying sizes that ranged between 1mm-500 μ m contained greater portion of the sediment sample. Also, grain

morphology results for the sandstone samples obtained show that about 26.3% of the total samples have very angular grains, while 13.2% have angular grains, and another 13% of the total samples have sub-angular grains. Likewise, 39.5% of the total samples have sub-rounded grains, while 7.9% has rounded grains (Figure 5.8). The overall results of grain morphology for 5 and 10 metres are summarised and presented in Tables 5.8 and 5.9 respectively.

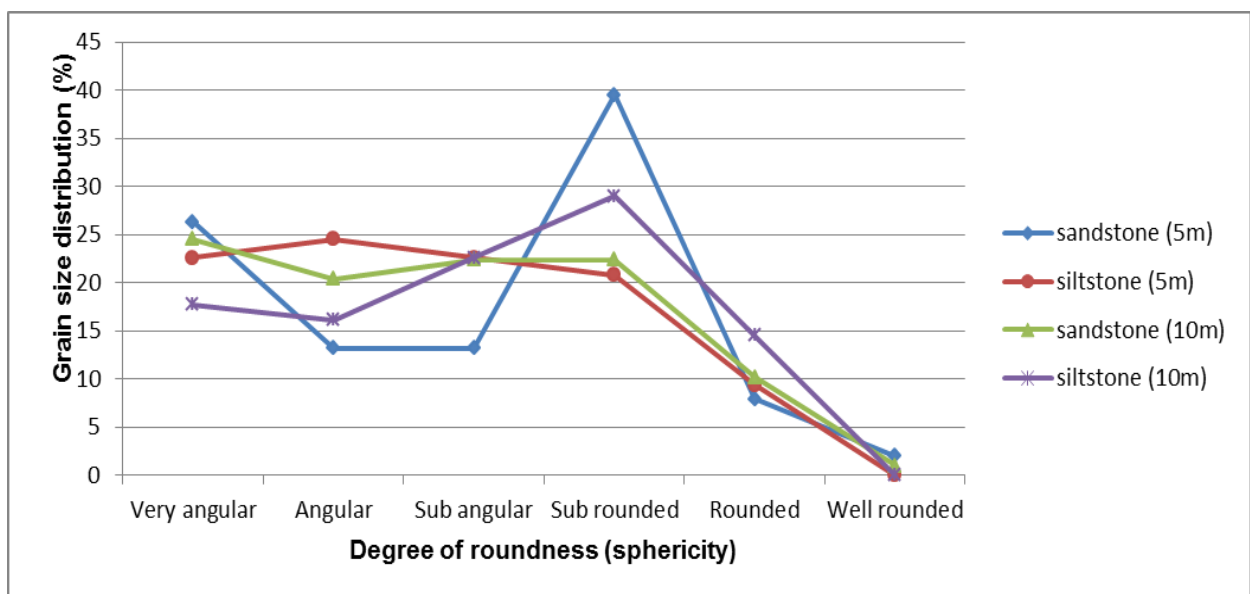


Figure 5.8 Grain Morphology analyses for Gwange area (site 2)

5.6 Pathway Mineralogical Composition Analyses Results

The modal composition analyses of the sediment samples in sites 1 and 2 indicated that the major mineralogical constituents of the sediments were; Quartz, orthoclase feldspar, Albite, microcline feldspar, zircon, iron oxide (Tables 5.8 and 5.9). Quartz and feldspar are the predominant minerals with quartz exceeding feldspar as Microcline feldspar and Albite also constitute moderate proportions in the samples.

Table 5.8 Modal Composition results for site 1(Percentage Composition)

Mineral composition	Site 1 sandstone (5m)	Site 1 sandstone (10m)	Site 1 siltstone (5m)	Site 1 siltstone (10m)
Quartz (SiO ₂)	35%	40%	44%	36%
Orthoclase feldspar (KAlSi ₃ O ₈)	29%	20%	19%	24%
Microcline feldspar (KAlSi ₃ O ₈)	20%	19%	14%	18%
Albite (NaAlSi ₃ O ₈)	10%	16%	14%	13%
Zircon (ZrSiO ₄)	-	-	2%	3%
Iron Oxide (Fe ₂ O ₃)	6%	5%	7%	6%

Table 5.9 Modal Composition results for site 2 (Percentage Composition)

Mineral composition	Site 2 sandstone (5m)	Site 2 sandstone (10m)	Site 2 siltstone (5m)	Site 2 siltstone (10m)
Quartz (SiO ₂)	40%	35%	39%	30%
Orthoclase feldspar (KAlSi ₃ O ₈)	29%	21%	22%	30%
Microcline feldspar (KAlSi ₃ O ₈)	16%	20%	20%	19%
Albite (NaAlSi ₃ O ₈)	11%	13%	17%	14%
Zircon (ZrSiO ₄)	4%	2%	2%	3%
Iron Oxide (Fe ₂ O ₃)	-	9%	-	3%

Table 5.10 Summary of particle size distribution (%) at the depth of 5m

	2mm	1mm	850µm	710µm	500µm	425µm	300µm	250µm	150µm	63µm	Pan
Max.	15.77	26.06	6.72	9.12	18.55	5.51	6.31	7.24	29.61	26.29	8.01
Min.	2.79	11.26	2.8	2.08	4.36	2.3	3.35	3.32	5.02	3.86	0.39
Avr.	9.36	18.45	4.67	5.70	11.52	3.99	4.67	5.11	17.01	14.94	3.65
Std.	7.07	7.80	2.20	3.94	7.76	1.65	1.45	1.96	13.52	12.49	3.61

Table 5.11 Summary of particle size distribution (%) at the depth of 10m

	2mm	1mm	850µm	710µm	500µm	425µm	300µm	250µm	150µm	63µm	Pan
Max.	13.36	10.81	13.1	12.11	13.42	8.8	8.1	9.91	25.6	22.1	7.12
Min.	1.99	7.7	3.1	3.9	3.8	3	2.89	4.5	3.21	2.99	0.61
Avr.	7.67	9.37	7.88	6.87	8.42	5.94	5.74	7.36	15.06	12.66	3.74
Std.	5.47	1.30	4.97	3.83	4.87	3.09	2.69	2.27	11.21	9.89	3.47

Table 5.12 Summary of grain morphology results at the depth of 5m

Location	Very angular	Angular	Sub angular	Sub rounded	Rounded	Well rounded
1	31.11	17.8	17.8	22.22	11.11	0
1	22.03	23.72	25.42	18.64	10.16	1
2	26.3	13.2	13.2	39.5	7.9	2
2	22.6	24.5	22.6	20.8	9.4	0
Average	25.5	19.8	19.7	25.2	9.6	0.75

Note: all values are expressed in percentage

Table 5.13 Summary of grain morphology results at the depth of 10m

Location	Very angular	Angular	Sub angular	Sub rounded	Rounded	Well rounded
1	26.41	20.75	15.09	24.52	13.2	0
1	16.7	14.81	24.07	29.62	14.81	1
2	24.5	20.4	22.4	22.4	10.2	1
2	17.7	16.1	22.6	29	14.5	0
Average	21.3	18	21	26	13.1	0.5

Note: all values are expressed in percentage

Table 5.14 Summary of mineral composition of sediments obtained at 5 and 10 meters depth

Depth	Quartz	Orthoclase feldspar	Microcline feldspar	Albite	Zircon	Iron Oxide	Accessory minerals
5 meters	38.5±0.03	24.7±0.04	17.5±0.02	13±0.03	2±1.4	3.25±3	1.01±00
10 meters	35.2±0.03	23.5±0.03	19±0.00	14±0.01	2±0.01	5±0.02	1.0±0.00

Note: all values are expressed in percentage

5.7 The Groundwater System

The groundwater of the upper aquifer of the study area occurs within the quaternary Chad formation; it is exploited via shallow boreholes, hand dug wells and tube wells. As shown by the model, this aquifer is subdivided into A and B zones in Gwange area (Figures 5.9). The depth to the water table in this area ranges between 6.40-15 metres depending on a particular location.

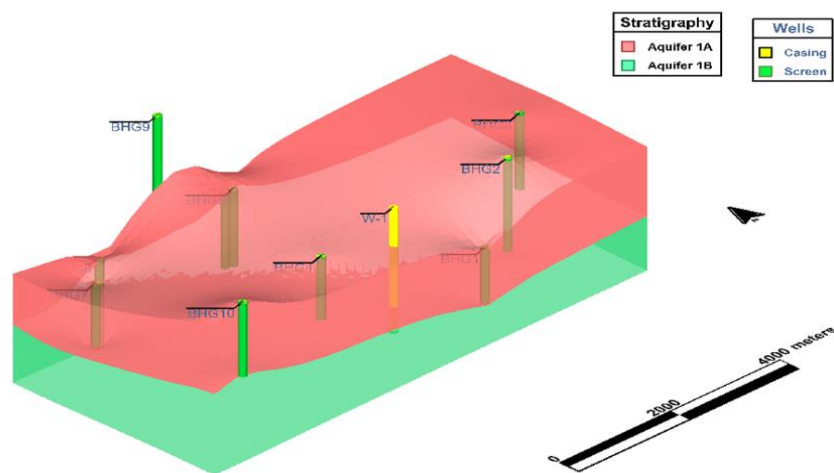


Figure 5.9 Conceptual representation of the upper aquifer in Gwange area

Contrastingly, in Moduganari area the upper aquifer is sub-divided into A, B, and C zones (Figure 5.10). Similarly, it is tapped via shallow boreholes and tube wells. The depth to water ranges between 2-17 metres.

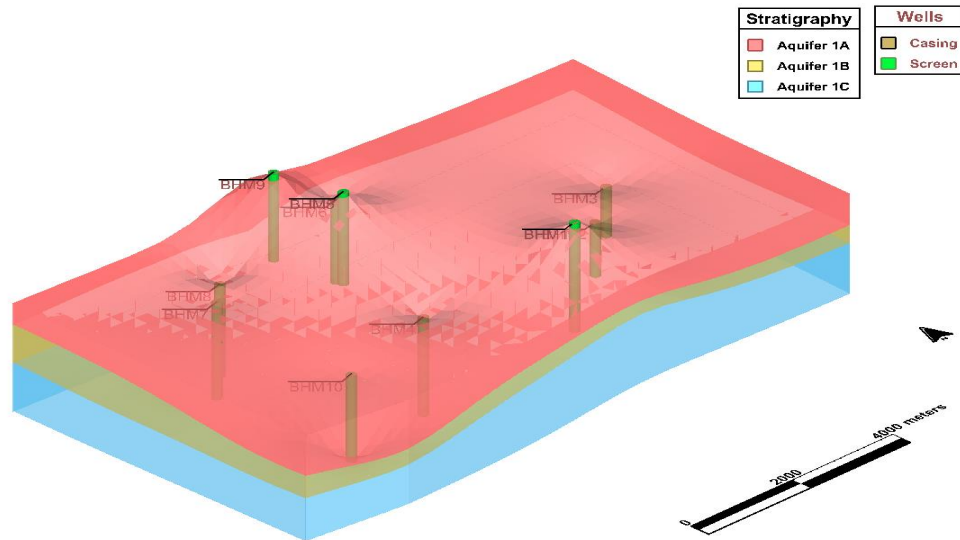


Figure 5.10 Conceptual representation of the upper aquifer in Moduganari area

5.7.1 Groundwater Quality

An investigation carried out by this study ascertains the current quality status of the groundwater of the study area due to the impact of the pollution sources evaluated in chapter 3.

5.7.1.1 Groundwater Physical Quality Results

The pH results obtained for the groundwater in site 1, range from 6.61 to 7.57 with an average of 7.76. In site 2, the result showed that the pH varies from 6.2 to 7.31 with an average of 6.81.

The obtained EC and TDS values for the groundwater in site 1 ranged from 123 to 200 $\mu\text{S}/\text{cm}$, and 85 to 175 mg/L . Their mean values are 169.8 $\mu\text{S}/\text{cm}$ and 146.8 mg/l ,

respectively. Also in site 2, the EC values ranged from 97 to 213 $\mu\text{S}/\text{cm}$. The mean value of the EC for site 1 is 168 $\mu\text{S}/\text{cm}$, while the amount of total dissolved solid in the groundwater varies from 103 to 181 mg/L with a mean value of 138 mg/L.

Respective minimum and maximum temperatures obtained for site 1 vary from 32.3 to 35.4°C, with a mean value of 33.6°C. That of site 2 varies from 26 to 32°C, with an average of 28.9°C.

5.7.1.2 Groundwater Chemical Quality (non-anthropogenic parameters)

Results

The concentration of the major cations show that the alkaline and alkali metals are dominant in all the groundwater samples of both sites; in site 1, Na^+ recorded highest and lowest mean values (25.2 and 10.5 mg/L) in BHM7 and BHM9 respectively; in site 2, Na^{++} recorded highest mean value (28.11 mg/L) in BHG6 and lowest (4.2 mg/L) in BHG1.

Also, highest and lowest concentrations of 28.5 and 18 mg/L were obtained in BHM8 and BHM5 for Ca^{++} in site 1. Similarly, in site 2, highest and lowest mean concentrations of calcium (26 and 7.65 mg/L) were recorded in BHG8 and BHG6 respectively. Likewise, in site 1, highest and lowest mean concentrations of 17.2 and 7.22 mg/L were separately recorded for K^+ in BHM3 and BHM6. In site 2, the highest mean value of 18.2 mg/l was obtained for K^+ in BHG3 while the lowest concentration of 4.94 mg/L was recorded in BHG6.

Additionally, the concentration of magnesium also varied across the boreholes in both sites. In site 1, the highest concentration is 14.6 mg/l in BHM9 (Figure 5.11), while the lowest is to 6.6 mg/l in BHM6. Furthermore, in site 2, magnesium recorded highest mean concentration of 15.1 mg/L in BHG10 and lowest concentration of 7.31 mg/L in BHG4.

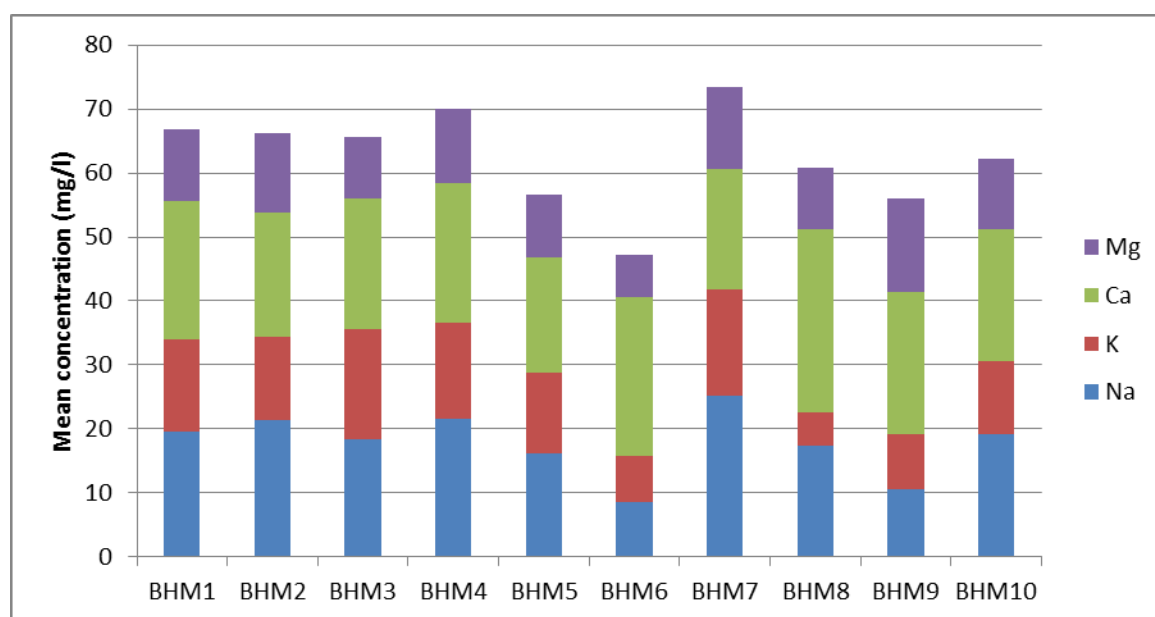


Figure 5.11 Concentration of cation in groundwater samples of Moduganari (site 1)

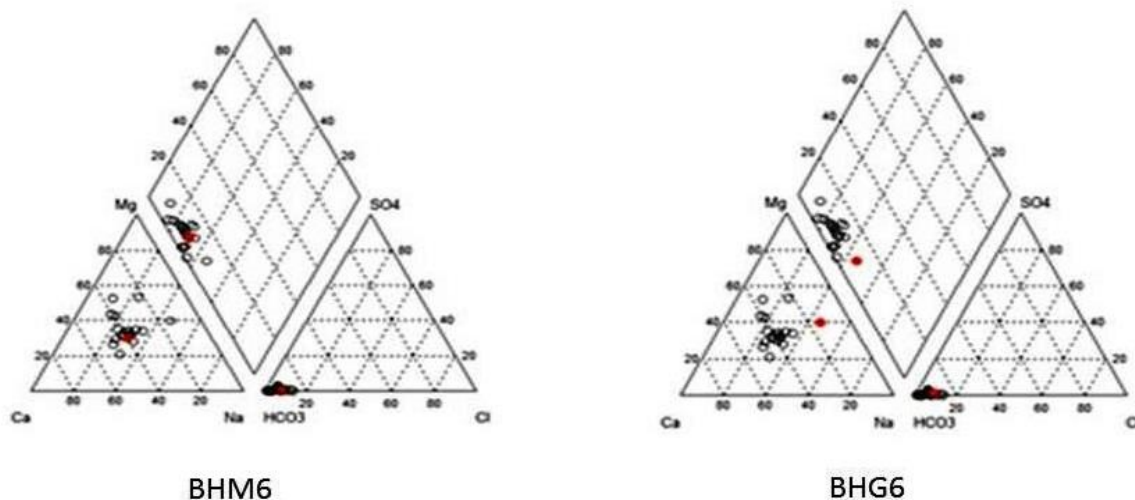


Figure 5.12 Trilinear plot showing concentration of cations and anions in two boreholes of sites 1 and 2.

The trilinear plot (Figure 5.12) shows that the concentration of the cations in the groundwater is within the WHO permissible limits (Table 5.15). Thus, the groundwater quality is good at present.

5.7.1.3 Groundwater Chemical Quality (anthropogenic indicator parameters) Results

Result of the groundwater quality analysis shows minor traces of contaminants such as nitrate, chloride, sulphate and phosphates which are mainly of anthropogenic origin.

Result show that; in site 1, nitrate is having varied concentration that ranged from 25.2 mg/l in BHM7 to 10.5 mg/l in BHM5. Similarly in site 2, nitrate recorded highest and lowest concentrations of 25.3 and 8.11 mg/L in BHG8 and BHG6 (Figure 5.13)

respectively. Likewise, in site 1, chloride recorded highest concentration of 16 mg/L in BHM1 and lowest of 2 mg/L in BHM7. In site 2, highest and lowest concentrations for Cl were recorded in BHG9 (Figure 5.14) and BHG4.

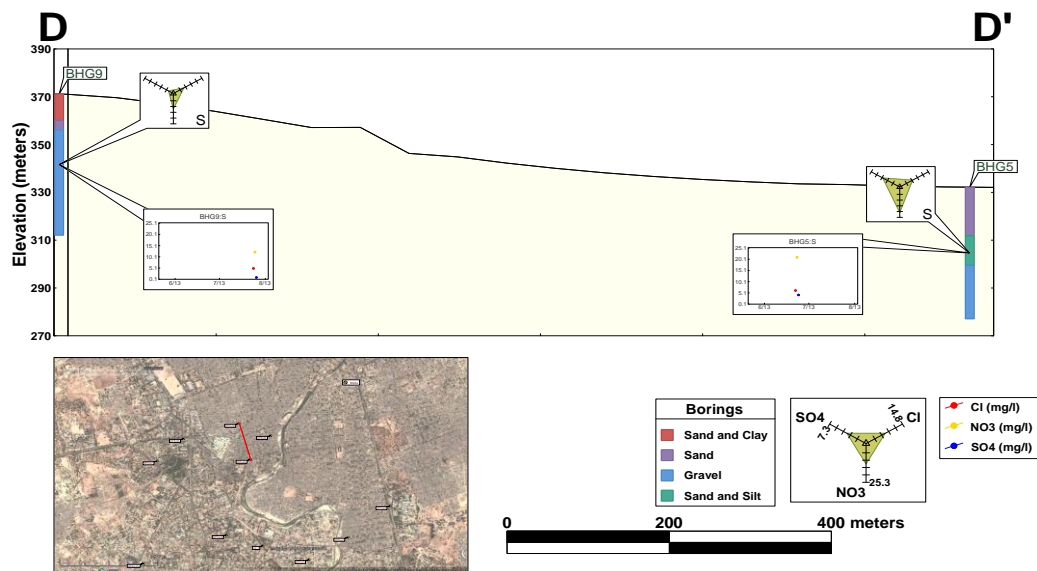


Figure 5.13 Cross section (D-D') showing boreholes 9 and 3 including their constituents' time series and radial diagram in Gwange area

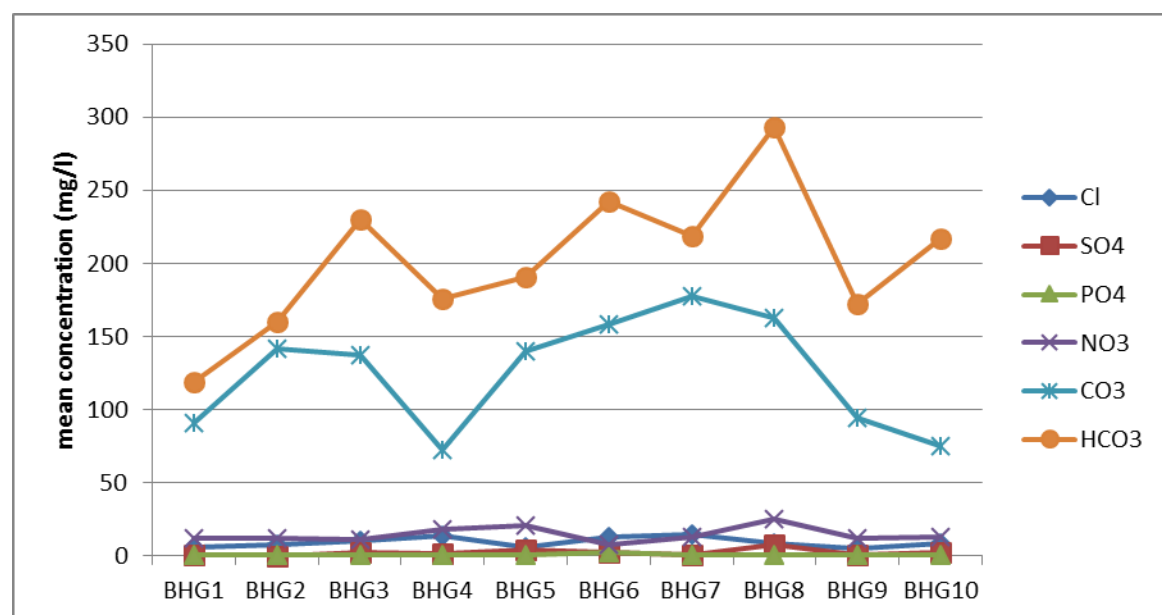


Figure 5.14 Concentration of anthropogenic indicator parameters in Gwange (site 2)

Table 5.15 Comparison of groundwater physico-chemical quality result of the study to established standards

Parameter	Unit	This study (average)		BGS/water aid (2003)	WHO limits
		Site 1	Site 2		
pH	-	7.15	6.8	-	6.5-8.5
EC		169.8	155.8	-	1500
TDS	mg/L	146.8	138.4	-	1000
Temp	°C	33.6	28.9	-	-
Na	mg/L	17.8	15.4	7.1-764	200
K	mg/L	12.1	10.5	-	30
Ca	mg/L	21.7	17.5	2.2-68	200
Mg	mg/L	10.94	11.1	-	150
Cl	mg/L	7.1	9.4	0.5-68	250
SO ₄	mg/L	1.3	2.2	<0.5-330	400
PO ₄	mg/L	0.56	0.8	-	200
NO ₃	mg/L	15.98	14.6	<0.4-102	50
CO ₃	mg/L	132.3	125.1	-	-
HCO ₃	mg/L	225.7	201.9	-	-

Table 5.16 Chemical parameters mean values with standard deviation for boreholes in site 1

Parameter	BHM1	BHM2	BHM3	BHM4	BHM5	BHM6	BHM7	BHM8	BHM9	BHM10
Na	19.6 ^c ±0.61	21.3 ^b ±0.87	18.3 ^{de} ±0.15	21.5 ^b ±0.11	16.2 ^f ±0.15	18.6 ^{cd} ±0.01	25.2 ^a ±0.20	17.3 ^e ±0.30	10.5 ^g ±0.10	19.22 ^{cd} ±0.01
K	14.3 ^d ±0.15	13± ^e 0.55	17.2 ^a ±0.58	15 ^c ±0.06	12.5 ^e ±0.10	7.22 ^h ±0.00	16.5 ^b ±0.06	15.3 ^c ±0.10	8.66 ^g ±0.01	11.3 ^f ±0.00
Ca	21.8 ^d ±0.06	19.6 ^f ±0.15	20.5 ^e ±0.06	22 ^c ±0.02	18 ^h ±0.10	24.8 ^b ±0.20	19 ^g ±0.06	28.5 ^a ±0.06	22.3 ^c ±0.05	20.6 ^e ±0.00
Mg	11.2 ^{de} ±0.06	12.4 ^c ±0.05	9.6 ^g ±0.15	11.5 ^d ±0.05	10 ^f ±0.05	6.6 ^h ±0.006	12.8 ^b ±0.06	9.7 ^g ±0.10	14.6 ^a ±0.25	11 ^e ±0.06
Cl	16 ^a ±0.05	4 ^d ±0.10	12 ^b ±1.00	10 ^c ±0.05	9.1 ^c ±0.05	3.2 ^{de} ±0.05	2 ^e ±0.06	10 ^c ±0.20	3 ^{de} ±1.00	2.2 ^e ±0.06
SO4	0.3 ^f ±0.05	0.07 ^h ±0.00	1.58 ^c ±0.03	0.17 ^{gh} ±0.05	3.1 ^b ±0.06	0.5 ^e ±0.10	0.24 ^{fg} ±0.06	5.47 ^a ±0.04	0.32 ^{fg} ±0.10	1.25 ^d ±0.00
PO4	0.12 ^h ±0.00	0.23 ^g ±0.00	0.46 ^e ±0.02	0.67 ^c ±0.05	0.78 ^b ±0.06	0.89 ^a ±0.00	0.34 ^f ±0.06	0.45 ^e ±0.01	0.54 ^d ±0.00	0.77 ^b ±0.01
NO3	12.6 ^{de} ±0.10	10.8 ^f ±0.70	17.7 ^c ±0.35	23.5 ^b ±0.05	10.5 ^f ±0.06	13 ^d ±0.06	25.2 ^a ±0.35	11.3 ^{ef} ±0.30	17.2 ^c ±0.20	18 ^c ±1.00
CO3	180 ^a ±1.00	132 ^c ±2.00	132 ^c ±1.00	181 ^a ±0.05	156 ^b ±1.00	132 ^c ±0.06	157 ^b ±0.60	84 ^e ±2.00	73.2 ^f ±1.00	97.63 ^d ±0.06
HCO3	183 ^b ±0.04	164.7 ^h ±0.60	250.2 ^c ±0.85	195.3 ^f ±0.35	244.1 ^d ±0.10	219.7 ^e ±0.75	268.5 ^b ±0.25	299 ^a ±4.00	168 ^h ±3.00	264 ^b ±1.00

Results are Mean of triplicates ± SD. Results on the same row followed by different superscript letter (a-h) indicate significant difference ($p \leq 0.05$) by (ANOVA) using Tukey grouping test.

Table 5.17 Chemical parameters mean values with standard deviation for boreholes in site 2

Parameter	BHG1	BHG2	BHG3	BHG4	BHG5	BHG6	BHG7	BHG8	BHG9	BHG10
Na	4.2 ^g ±0.44	13.5 ^e ±0.27	17.6 ^c ±0.26	11.3 ^f ±2.14	15.4 ^d ±0.48	28.11 ^a ±1.25	23 ^b ±0.96	16.31 ^d ±0.61	11.53 ^f ±0.50	12.86 ^e ±0.46
K	8.03 ^{ef} ±0.11	12.2 ^c ±0.42	18.2 ^a ±0.15	7.4 ^f ±0.49	10.4 ^d ±0.40	4.94 ^h ±1.09	14.99 ^b ±0.28	14.5 ^b ±0.39	8.3 ^e ±0.35	6.04 ^g ±0.05
Ca	10.5 ^{cd} ±0.45	21.03 ^b ±1.07	23 ^b ±0.42	13.1 ^c ±0.10	19.6 ^b ±0.39	7.65 ^d ±1.39	22.4 ^b ±0.59	26 ^a ±3.75	21.1 ^b ±0.07	10.7 ^{cd} ±0.60
Mg	9.5 ^h ±0.55	10.8 ^e ±0.02	11.2 ^d ±0.03	7.31 ⁱ ±0.42	9.77 ^g ±0.05	13 ^c ±0.16	10.1 ^f ±0.02	10.2 ^f ±0.03	13.9 ^b ±0.09	15.1 ^a ±0.90
Cl	6.4 ^g ±1.47	7.5 ^f ±0.45	10.12 ^d ±0.07	13.7 ^b ±0.47	6.2 ^g ±0.15	12.9 ^c ±0.59	14.8 ^a ±0.56	8.9 ^e ±0.06	4.95 ^h ±0.16	8.6 ^g ±1.03
SO4	0.51 ^c ±0.04	0.12 ^f ±0.02	2.14 ^c ±0.02	1.32 ^d ±0.49	4.2 ^b ±0.04	2.6 ^c ±0.53	0.53 ^{ef} ±0.06	7.3 ^a ±0.06	0.91 ^{de} ±0.09	2.14 ^c ±0.04
PO4	0.36 ^d ±0.02	0.29 ^e ±0.02	0.42 ^{de} ±0.01	0.98 ^b ±0.15	0.78 ^c ±0.02	2.6 ^a ±0.56	0.48 ^d ±0.03	0.54 ^d ±0.01	0.81 ^c ±0.02	0.92 ^{bc} ±0.02
NO3	12.5 ^d ±0.84	12 ^d ±0.14	10.9 ^e ±0.13	17.9 ^c ±0.06	21 ^b ±0.11	8.11 ^f ±0.76	13.3 ^d ±0.24	25.3 ^a ±0.89	12.2 ^d ±0.30	12.9 ^d ±0.02
CO3	91 ^f ±2.00	142 ^d ±1.52	137 ^d ±1.52	72.7 ^f ±1.52	140 ^d ±1.00	158 ^c ±1.00	178 ^a ±2.51	163 ^b ±3.05	94.3 ^e ±1.52	75.1 ^f ±1.50
HCO3	119 ⁱ ±0.53	160 ^g ±0.80	230 ^c ±0.58	176 ⁱ ±1.73	191 ^d ±2.08	242 ^b ±0.70	219 ^e ±0.49	293 ^a ±2.51	172 ^f ±1.00	217 ^h ±1.00

Results are Mean of triplicates ± SD. Results on the same row followed by different superscript letter (a-h) indicate significant difference ($p \leq 0.05$) by (ANOVA) using Tukey grouping tes

Also, in site 1 of the study area, sulphate has highest and lowest concentration of 5.47 and 0.07 mg/L in BHM8 and BHM2 respectively, while phosphorous recorded highest concentration of 0.89 mg/l in BHM6 at the same site and lowest concentration of 0.12 mg/L in BHM1 (Table 516). Similarly in site 2, sulphate has highest mean concentration of 7.3 mg/l in BHG8, and BHG2 has the lowest sulphate concentration of 0.12 mg/l (Figure 5.15); also in the same site, phosphorus has highest concentration of 2.6 mg/l and lowest of 0.29 mg/L in BHG6 and BHG2, respectively.

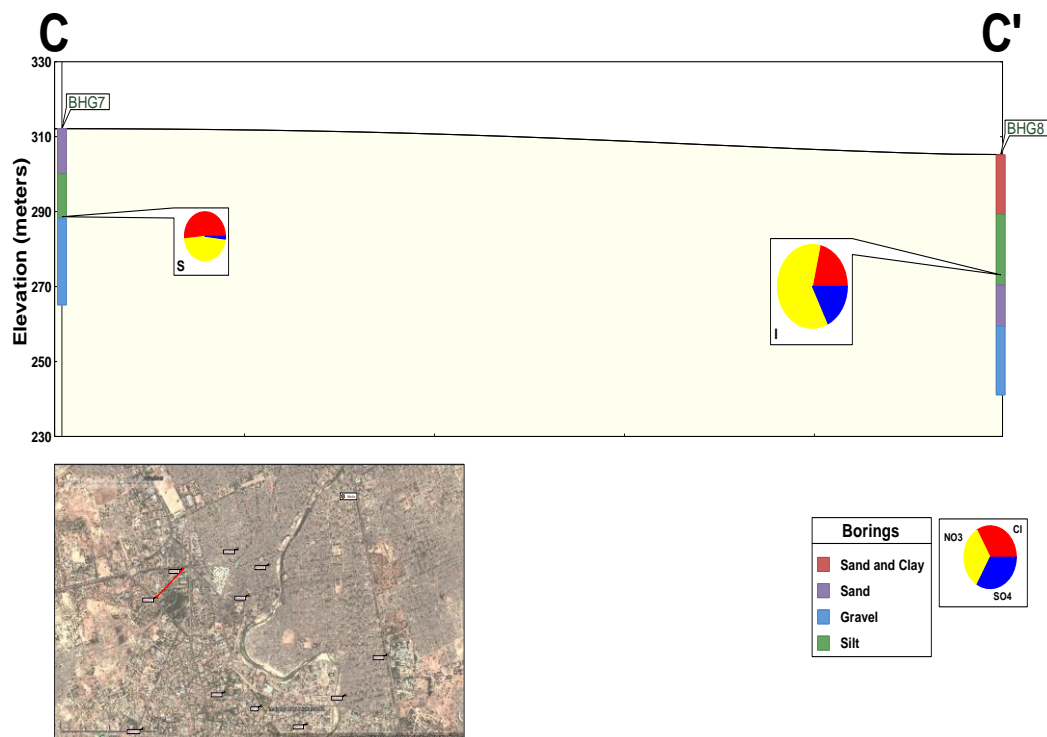


Figure 5.15 Cross section (C-C') showing profile of boreholes 7 and 8 including their constituents (anions) in Gwange area

5.7.1.4 Groundwater Chemical Quality Concentration of Other Ions

The concentration of other ions such as carbonate and bicarbonate in groundwater of both sites vary considerably; in site 1 the concentration of bicarbonate vary between 299 and 164 mg/l in BHM8 and BHM2 respectively; in site 2 it varies from 293 mg/l in BHG8 and 119 mg/l in BHG1. Similarly the concentration of carbonate varies considerably across the boreholes of the two sites; in site 1, lowest concentration of 73 mg/l was recorded in BHM9 and the highest of 181 mg/l in BHM4. In site 2, lowest and highest concentrations of 72 mg/l 178 mg/l were recorded for BHG4 and BHG8 respectively.

5.8 Discussions

This section provides a detailed discussion on the results of both the social and hydrogeological dimensions. Sub-section 5.8.1 presents the social aspects discussion, while sub-section 5.8.2 presents the hydrogeological aspects discussion.

5.8.1 Discussion of social aspects

More frequently, the quantity of water used is related to the household size and household income, hence the households with highest number of inhabitants and those with high income are likely to consume significant volume of water in the study area. In view of this, AICD (2011) reveals that annual income of most individuals inhabiting less affluent settlements in Sub-Saharan African countries and other developing nations is often generally low. In the study areas, the situation is not quite

different. This skewed income distribution can be attributed to the differences in socio-economic activities of the various households. The low to moderate income earnings in these areas will also have implication for the willingness to pay for the provision of extra sanitation activities and this will ultimately affect the sustainability of managing wastes generated.

Likewise, in Sub-Saharan Africa most households are relatively large because of the polygamous and extended family structure. However, this century long tradition is presently losing popularity due to the economic liability associated with it, and modernism. Household size has implication for the amount of wastes generated and the quantity of water consumed per day. Considering the existing low level of sanitation facilities in the study area, household wastes generated are often left unattended by communities.

A discussion of the issues identified, building on the findings of Bakari et al. (2014), shows that environmental problems, impacting negatively on groundwater resources, are widespread in the study area, so accordingly most interviewees are familiar with these issues, at least at a basic level. However, in a few instances some of the interviewees failed to give convincing accounts of these issues. The interviewees from academia, ministries of Water, Environment and Health were the most knowledgeable; likely related to their high level of education and professional involvement in dealing with environmental issues in their respective roles. Despite the differences in their understanding, all interviewees were keen to be involved in addressing the environmental problems; this is probably because they are in a

position of authority, hence they see it as a vested responsibility as far as their organisations are concerned.

Conversely, awareness about groundwater contamination is very limited in the general population focus group category. Participants in this category are typically individuals with little relevant education such as farmers, local business owners and traders that constitute the bulk of the urban, less-affluent populace. Similarly, the household survey revealed that most of the respondents are not knowledgeable about groundwater contamination; with more than 87% (n=288) of the households unfamiliar, only a minority (12.2%) of the respondents are informed about this issue. Survey results clearly indicated a low level of environmental awareness among the general populous.

The majority of those interviewed from a relatively highly educated background were worried that consuming contaminated groundwater can be very harmful to human health. The respondents from the relatively poorly educated background typically showed little interest in issues related to the causes of groundwater contamination in their respective areas. It can be generally observed that level of education is a decisive factor in showing concern for the environment.

Public health issues are universally of greater concern than the environment. In general interviewees were wary of the effect of consuming contaminated water because of their familiarity with health risks. Water-related illnesses are prevalent in

most developing countries, particularly in sub-Saharan Africa. The general lack of concern over groundwater contamination, among poorly educated focus group participants/survey respondents, was related to the potable status of their current water supplies. It also however relates to their increased concern of other socio-economic issues which affect their lives, in particular poverty. In this context, it is important to note that most participants and households surveyed live on less than the global benchmark of \$1 per day, indicating extreme poverty. As previously noted the poor level of education plays a significant role in the ability of low-income individuals to make informed decisions on issues related to groundwater contamination.

The common causes of groundwater contamination drawn from the interviews and focus groups are largely due to the widespread utilisation of pit latrines and open dumpsites, commercial activities and agricultural practices. Domestic and commercial wastes are prevalent and widespread, while agricultural wastes are also generated, albeit in smaller amounts. The population density is estimated to be around 300-400 inhabitants per square kilometre, with a high number of inhabitants per household. The household survey revealed that 48.3% of the respondents affirm that pit latrine is the biggest causal factor of groundwater contamination, open dumpsites was next in rank with 28.5%; other sources such as domestic wastewater, tanneries, dyeing works constitute about 15.3%, and chemical and fertiliser application upstream of the residential areas make up the remaining 8.0%.

Open dumping and burning of all forms of waste in pits and in open spaces are common. The preference of these methods in the area has been practiced for a very long period. As previously identified it is obvious that the general public have little regard for the environment due to the predominant lack of awareness. Adequate waste collection facilities are lacking, and this has greatly influenced the attitude of the people towards poor waste disposal practices. Thus, it can be concluded that an attitude of indiscriminate waste disposal exists among the people.

The prevalence of these contamination sources in the study area is due to the cultural affiliation of the people towards on-site sanitation facilities, the unequal service provision rendered by the government, poverty, low level of public awareness, and lack of hygiene education among others. Thus, reversing these trends will require a shift from the current system to a more integrated and sustainable one.

5.8.1.1 Other issues stressed by stakeholders

Other issues highlighted by the institutional stakeholders include, low capacities by the local water user groups, poor institutional collaboration at both state and national levels. This has resulted in overlapping of functions between the three tiers of government and their agencies. Also, the study has identified a huge gap at the institutional levels; poor knowledge about modelling tools for decision making. Taking into consideration, existing conflicting institutional irregularity between the different agencies has undesirably affected the efficiency of water supply in the entirety of the case study area.

The above statement is in line with the judgement of the Word Bank (2012) that poor coordination between the National and regional level as well as among different water agencies and allied organisations is a major constraint in achieving sustainable groundwater management in developing countries. Hence, the different approaches adopted by the various agencies responsible for water supply have undermined the utilisation of groundwater resources in Nigeria. This is in harmony with the investigations of Hanidu (2003) and Goni (2006) in the country.

Other key impediments for institutional sustainability according to the institutional stakeholder's include shortage of skilled manpower for the development of appropriate local technology and the adoption of new technologies. Conversely, the availability of a sizeable number of qualified manpower to deal with hydrogeological, engineering, environmental and managerial aspects of groundwater resource management is extremely low in the case study area. This component is paramount in achieving sustainability. Another important issue related to technical problem is the lack of reliable management information system and monitoring network. Goni (2006) and Offodile (2006) argued that the number of well-trained professionals (hydrogeologists, water engineers, and technicians) responsible for handling and managing water projects is extremely low.

Lastly, the stakeholders attest that inadequate funding is a major problem in Borno state; funds and subvention allocated to the state ministry of water resources are extremely insufficient, considering its current low level of operation and the ever increasing water demand across the state. In this regard, the current insufficiency

funding has affected the maintenance and repair of ageing utilities, spare parts of water works, boreholes pumps and generating sets in the case study area (Bakari and Jefferies, 2013). In relation to this, the AICD (2011) carried out an investigation and confirmed that most utilities across Nigerian cities operate poor infrastructure and about two-thirds of Africa's urban population is served by ageing water utilities.

Adequate funding is not available to the public water agency for expansion or rejuvenation of its ageing infrastructure in the case study area; expansion of urban utilities in Nigeria could not keep up with the population growth due to poor budgetary provision for the water sector by all the three tiers of government in the country. Funding issues in the water sector is a major problem in Nigeria and in most developing countries. This situation conforms with the view of Lloyds (1994) that funding of water schemes in developing countries is often difficult and extremely hard to obtain. This issue have been highlighted by Offodile (2003) and Tijani (2006) in Nigeria. Also inadequacies of funds affect the maintenance and expansion of water utilities across the country; this is in agreement with the judgment of Helwig (2000).

5.8.2 Discussion on hydrogeological aspects

5.8.2.1 Pollution Pathways

The pore spaces of the overlying sedimentary formation (the Quaternary Chad Formation) are the most probable pathways through which contaminants travel into the underlying aquifers. The stratigraphy of the study area is mainly constituted of sand, silt and clay, and gravel in descending order. This chronological arrangement seems to suggest fluvial depositional sequence, the gravelly nature of the lower unit suggest sedimentation under high energy environment with the upper silt and clay units deposited later as the energy of the transporting medium subsided, gravelly materials thus being deposited at the base.

The degree of angularity of the sediment samples, as highlighted in the results, expresses the ratio of the average radius of curvature of the edges of the respective grain classification categories to the radius of curvature of their maximum inscribed sphere. The dominance of angular and very angular grains as presented in the grain morphology analyses probably had direct relationship with the attenuation capacity of the sediments of the study area; thereby increasing the attenuation capacities of the sedimentary unit which provide protective cover for the upper unconfined aquifer system.

Arguably, it is possible that the heterogeneity and complexity of the sediment's interlocking pattern restricts the vertical movement of contaminants, thereby affecting

the fate of anthropogenic contaminants within the geo-system and hence the limited amount of contaminants in the groundwater. However, it is noteworthy that fractures and secondary pore spaces that exist within the geo-system can be a potential pathway for contaminant migration and movement in the sub-surface.

5.8.2.2 Groundwater Physical Quality

pH is a measure of the hydrogen ion concentration in solution and is also referred to as the degree of acidity or alkalinity. The distribution of pH for the two areas suggests that the groundwater in site 1 is alkaline while that of site 2 is acidic-alkaline in nature. Both mean pH values obtained are within WHO permissible limit. The alkalinity and acidity of the pH values in both sites may be due to the presence of dissolved carbon dioxide and organic acids (fulvic and humic acids) in the groundwater, which might be derived from the decay and subsequent leaching of plant materials and other biological processes (Langmuir, 1997; Stuart and Reeder, 2008).

Also, the relatively low to moderate values of EC and TDS in both sites signifies lower residence time of ground water within the Chad formation; this is because the upper aquifer is continuously recharged by rainfall; which causes significant dilution. Also, the occurrence of low EC values indicates a low degree of mineralisation and input from the agricultural activities upstream of both sites. Consequently, the low TDS values also suggest that inputs of salts from the anthropogenic sources of pollution in both sites are minimal.

The temperature of the groundwater of the study area is slightly higher than the natural background levels of 22 to 29°C for waters in the tropics which is not preferred. Mostly, cool waters are more potable for drinking purposes; waters with temperature above the normal human body temperature are usually preferred in the tropics, though not totally objected. High temperature conditions may not be desirable for water samples as it encourages the growth of micro-organisms, which have the potentials of altering the odour, taste and colour to the water (Stumn and Morgan, 1981). Metal corrosion problems are also associated with high temperature especially when the pH of the water happens to be skewed to extreme.

5.8.2.3 Chemical Quality non-anthropogenic Parameters

The distribution of sodium, calcium, potassium and magnesium indicates that their concentrations across all the samples of both sites are significantly different ($p < 0.05$) across the various boreholes. The results suggest that natural processes occurring within the geological formations such as ion-exchange processes, silicate weathering and calcium carbonate dissolution are the major factors affecting their concentration in varying proportions in the groundwater samples of the study area (Lakshmanan et al., 2003).

5.8.2.4 Chemical Quality Anthropogenic Indicator Parameters

In both sites, the concentration of chloride varied across the boreholes ($p < 0.05$). The source of chloride in the study area can be correlated with the widespread

anthropogenic point-source pollution sources such as the widespread occurrence of pit latrines, open dumpsites, and the uncontrolled domestic wastewaters emanating from the cluster of informal settlements of the case study area, as well as agricultural inputs from upstream manure application in farm lands. Nolan et al. (2002), Squillace et al. (2002) and Singleton et al. (2005) estimate that chloride concentration in the range of 13 to 18 mg/l indicate anthropogenic input.

The variation in concentration of chloride in site 1 is due to the location of a dumpsite in the south-eastern part of the area, while the borehole (BHM5) furthest away from the dumpsite is having minimal concentration of chloride, thus, this showed significant difference in their concentration. Hence, the dumpsites have impacted negatively on the groundwater system. This is also true for site 2, where elevated chloride concentration was observed in the borehole (BHG8) located in the western part of the area (dense pit latrine concentration), and the lowest concentration was found in the northern part which receives less impact (less dense). These differences can be related to the dissimilarity of anthropogenic activities in the two locations; the former location receives high chloride probably because it is very close to the river Ngadda Bank where huge amount of solid wastes are disposed in dumpsites, and residential areas served by pit latrines.

Elevated concentration (> 250 mg/L) of chloride in waters is an indication that the waters are at the risk of pollution (Atabey, 2005). The levels of chloride in waters are of particular importance for use in drinking water. Also, chloride ions can be introduced as atmospheric inputs from rainfall recharge. The latter assumption was validated by a previous study carried out by Edmunds et al. (1999), where they

measured chloride concentration of 2.1 mg/l in the present day rainfall of the study area.

Also, Edmunds and Street-Perrott (1996) and Gaye and Edmunds (1996) have analysed the rainfall chemistry in this region and estimated concentration of chloride as 1.28 and 0.61 mg/l for dry and wet seasons, respectively. The moderate level of chloride in all the samples of sites 1 and 2 suggests that the anthropogenic input due to the furthest distance of this inland aquifer from the coastal zone where chloride concentration is very high.

Thus, the concentration of both sulphate and phosphorous varied and hence concentrations are significantly different ($p < 0.05$). Sulphate occurs naturally in geological materials, in igneous rocks; sulphur occurs mostly as metallic sulphides and is fairly distributed in the various rock types. In arid sedimentary basins, the highest abundance is in gypsum and anhydrite (van Helvoort et al., 2009). The main anthropogenic sources of sulphate in groundwater of the study area can be attributed to application of agrochemicals, the mining of gypsum in the western part of the Basin and contemporary acid rain (Quevauviller et al., 2009). However, in the study area, Goni et al. (2001) have analysed the rainfall geochemistry of the region, and posits that sulphate in the region is derived from atmospheric mixing of aerosols, and from ash of burnt forests.

Anthropogenic sources of phosphate in the study area include human sewage and the routine use of non-biodegradable detergents. As a result of the monotonous agricultural activities up stream of both sites especially near the Lake Alau Dam and

Biu/Damboia Road, phosphates derived from the application of fertiliser in these areas are continuously added to soil and leaches to underlying aquifers gradually as observed during the field work. Long-term over-application of manure and chemical fertiliser has been known to contribute to phosphorus movement into the groundwater system (Domagalski and Johnson, 2012).

5.8.2.5 Concentration of other Ions

The bicarbonate and carbonate ions in the groundwater samples of both sites originate from the solution of CaCO_3 in groundwater made by acid dissolving CO_2 gas from the atmosphere and soil. Also, their concentration can be linked to the dissolution and ion exchange processes occurring within the huge limestone deposit sources in the south-western part of the Basin.

5.9 Summary and conclusion

This chapter presented the views and opinions of both strategic and primary stakeholders in addressing the issues of groundwater contamination in the case study area. Stakeholder's knowledge, opinions and concerns with respect to environmental problems are explored in this regard. Knowledge about groundwater contamination issues is very high among the strategic stakeholders interviewed; and they are keen to be part of addressing this problem. Also, awareness and concerns on the above-mentioned issue is unconvincingly low among the primary stakeholders engaged via focus group and household surveys.

According to all the categories of stakeholders engaged, the major environmental problems occurring in the case study area are principally related to anthropogenic activities; the proliferation of pit latrines, incessant waste disposal, and other non-point sources of contamination across the city. Accordingly, pit latrines and open dumpsites constitute the highest negative impacts on groundwater resources of the case study area. None of the stakeholders mentioned industrial sites as sources of contamination. Likewise, all the stakeholders confirm that residential and commercial wastes from local businesses are dominating the scene. Lastly, open dumping, burying in pits, and burning are the most preferable waste disposal methods in the case study area.

Also, other important issues acknowledged by the participants of the interview include funding issues, and the inadequacy of technical and human capacities. Hence, capacities to deal with pollution threats are extremely insufficient and needed to be strengthened. This can be ensured by training members of staff on water quality issues and implementation of groundwater monitoring networks. On the other hand, sensitisation of the general public about pollution threats, identification of potential threats to groundwater systems will enhance their capacities. Furthermore, the stakeholders suggested that the problems can be addressed through active community participation, increase in investment, controlling waste from the source, and strict legislations.

Almost all the institutional stakeholders engaged are of the view that there is no evidence of contamination in the study area. Likewise, despite their limited knowledge about groundwater contamination, the water user groups engaged via

focus group discussions and household surveys confirmed that they are not affected by groundwater contamination problems. Table 5.18 below presents the major summary from the social engagement aspect of this study.

Table 5.18 summary of key points opined by the various stakeholder groups

Stakeholder category	Engagement strategy	Key points/ opinions
<i>Institutional stakeholders</i>	<i>Interviews</i>	<p>Stakeholders are knowledgeable about issues related to groundwater contamination</p> <p>The groundwater quality is currently good and safe for consumption</p> <p>Concerns about groundwater contamination is extremely high</p> <p>Major environmental problems are due to the influence of anthropogenic activities</p> <p>Pit latrine and open dumpsites constitutes the highest impact</p> <p>Funding in the water sector is limited</p> <p>Technical and human capacities to curtail contamination are low</p> <p>Poor institutional collaboration at local, state and federal levels. Hence the need for further commitment and streamlining of responsibilities</p> <p>Current legislations are weak and existing approaches to waste management are inadequate</p>

***Primary stakeholders as
water user groups***

Focus groups

Knowledge about
contamination is very low

Concerns about groundwater
contamination is extremely
low

Participants confirm that pit
latrines and dumpsites are
the major perceived sources
of contamination

Participants are not affected
by issues of groundwater
contamination

Open dumping and pit burial
is the most common waste
disposal method

Wastes generated are
commonly residential and
commercial

***Local residents as water
user groups***

Household survey

Wastes generated are mostly
from local businesses and
households

Dumping on land, in
drainages and communal bin
are the preferred options.
Other mode of disposal
includes burial, burning and
the use of old wells

Household respondents are
unaware of any issue related
to groundwater
contamination

Respondents are not
affected by problems of
groundwater contamination

Households were of the

opinion that both government and private investment in the water and sanitation sector is needed

Respondents are not willing to pay for any amount in exchange of improved services

Respondents are of the opinion that community participation is the best strategy for addressing the current problem

Statistical relationship exists between household income and willingness to pay for extra sanitation services by respondents

Statistical relationship exists between awareness about groundwater contamination and the education status of respondents.

There is statistical relationship between household level of education and respondents awareness on the implication of dumping of waste

Household respondents opted for increase in investment in water sector, introduction of strict laws, community participation and controlling of wastes as the viable ways of attaining sustainable system

Furthermore, groundwater contamination can be attributed to the above-ground anthropogenic activities especially pit latrines and open dump sites. The chapter concludes that sediments pore-spaces control the vertical movement of contaminants. However, the fractures and secondary pore spaces due to continued geological processes can be potential pathways for contaminant migration and movement in the sub-surface.

Additionally, the potential sources of anthropogenic contamination in the case study area include the proliferation of pit latrines, incessant domestic and municipal waste disposal. The concentration of sodium, calcium, potassium, and magnesium indicates that they are occurred due to silicate weathering processes occurring within the hydrogeological environment. Typically, this process is dominant in a sedimentary environment with abundant clastic materials. The concentrations of the above named non-anthropogenic parameters are well within the WHO safe limit for consumption and their levels are consistent with the natural occurrence levels of the key elements that make up the aquifer material. Thus, they are correlated with the mineral content analysis result.

Also, the concentrations of chloride, nitrate, phosphate, and sulphate are far below the limits set aside by WHO for safe consumption. In this respect, chloride recorded average concentration of 9 mg/l in the case study area, while nitrate recorded 17 mg/l, sulphate recorded 2.77 mg/l, and phosphate recorded 1.01 mg/l. In this respect, the WHO safe limit for chloride is 250 mg/l, sulphate is 400 mg/l, phosphate is 300 mg/l, and nitrate is 50 mg/l.

Overall, the hydrogeological investigation of this study confirmed that the groundwater quality is presently good. This validated the opinions of the strategic stakeholders. In furtherance to this, the next chapter investigates the fate of chloride (as a contamination indicator parameter) in the hydrogeological environment and develops the alternative guidelines for mitigating contamination of aquifers. This is aimed at achieving the overall objectives of the study.

This chapter presented and discussed the results from the social and hydrogeological dimensions; the next chapter (6) presents the aspects of chloride modelling and the development of the new guidelines applicable in the case study area.

CHAPTER 6

MODELLING CHLORIDE CONTAMINATION AND NEW GUIDELINE DEVELOPMENT

6. Introduction

The previous chapter focused on the social and hydrogeological aspects of the study. This chapter is divided into two components; the first part presents the modelling of chloride contamination due to the impact of above pit latrines. The second part presents outlines the development of the new guidelines for mitigating the impact of pit latrine on the underlying aquifer in the study area. The rationale for carrying out the modelling is to predict the behaviour/occurrence of contaminants based on the source-pathway scenario and, to enable develops sustainable guidelines in the case study area. In this respect, the MODFLOW/ MT3DMS code was implemented to achieve the above mentioned modelling. Vital hydrogeological (primary and secondary) data were obtained from different sources for the modelling exercise. Likewise, secondary data from the World Bank and UNICEF/WHO reports were used for comparison of (guidelines) global standards to those developed by the study. This provides a framework within which practical solutions of achieving sustainable groundwater management can be implemented; in line with the overall aim of the study.

6.1 Modelling chloride contamination due to pit latrine impact

In order to investigate the impact of pit latrine on groundwater resources of the case study area, a modelling was conducted with processing MODFLOW/MT3DMS software to demonstrate the possibility for chloride contamination of the shallow aquifer due to the influence of above-ground onsite sanitation system. MODFLOW/MT3DMS was used because it includes an implicit iterative solver based on generalised conjugate gradient (GCG) that implicitly solves advection, dispersion, and sink source without any restrictions. The general purpose of the modelling in this study is to help address groundwater contamination problems, design valuable contamination mitigation strategies, and provide information for decision making.

In achieving the objectives of the modelling, a reference borehole (BHM1) with the highest chloride concentration of 16 mg/l (see Table 5.16 in chapter 5) was selected to conceptualise the system (Figure 6.1). The justification for selecting chloride as an indicator parameter is provided in section 2.8.17. The study area is characterised by water table ranging between 10-15 m below the bottom of the pit latrine. Important hydrogeological parameters for the local case study area which are required by MODFLOW were collected from different sources (existing literature, the Borno State Water Agency, Nigeria Hydrological Services Agency, and primary data of this study). Other information such as pit latrine characteristics, number of latrine users and their frequency was obtained via a follow-up survey.

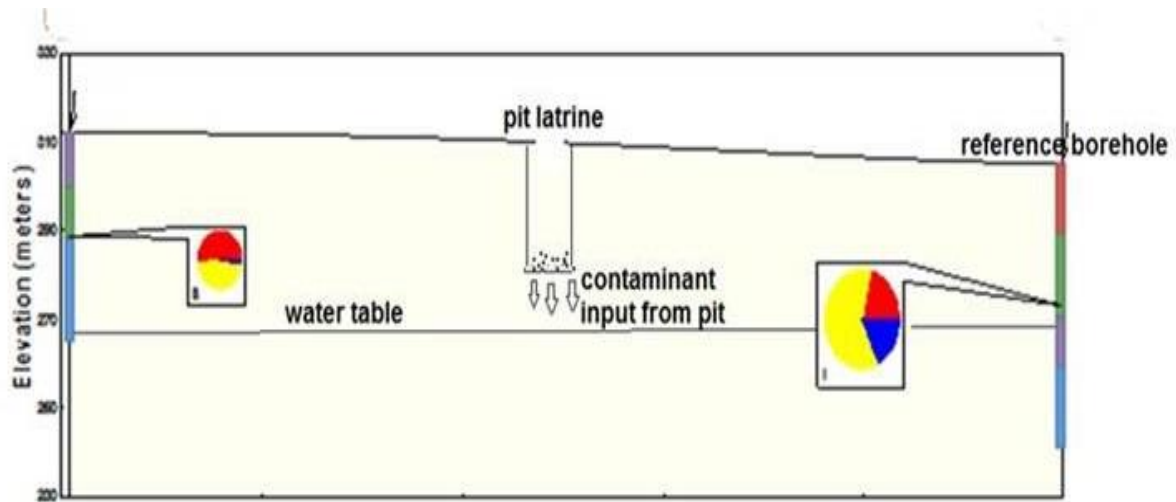


Figure 6.1 Conceptual model showing the impact of pit latrine on groundwater

In carrying out the modelling, a representative model domain with 25 columns and 50 rows was selected. The modelled aquifer dimensions are 800 m in length, 200 m wide and 25 m deep. It was confirmed through the survey that there was an average of 15 users per pit latrine. The water flux and soil moisture of the study area were documented as 0.002 and 0.3 m³/ m²/day respectively; hence the pore velocity is 0.01 m/day. These values were obtained for the sediments of the study area by gravimetric methods (NIHSA, 2013).

The retardation coefficient for chloride was assumed to be 1.0, dispersion assumed to be 2.4×10^{-7} m²/s (Fetter, 1994). The hydraulic conductivity of 0.0002 m/s and 0.0006 m/s was measured for units A and B respectively by previous studies (Goni et al., 1996 and Akujieze et al., 2003). The effective porosity of the aquifer is set in the MODFLOW model as 30 percent (the maximum equated effective pore space for clastic sediments). The study adopted an estimated recharge of 0.0001 m³/ m²/ day.

This was calculated for the study area; the value was estimated by means of using chloride mass balance method by Goni and Edmunds (2006).

According to the British Geological Survey (BGS, 2002) each person excretes about 4g of chloride per day (urine 90–95%, faeces 4–8%, and sweat 2%). Taking this into consideration, if we multiply this estimate by the total number of latrine users per pit (15 people per day) latrine and the total number of households (300) in the modelled site, we will have chloride concentration of about 18000 mg/l within the modelled domain. Lastly, a chloride half-life of 190,000 days (Bentley et al., 1986) was considered for this study.

6.1.1 Modelling approach

In providing quantitative assessment of the impact of pit latrine on the underlying aquifers of the case study area, an integrated modelling approach that combines the outputs from MODFLOW/MT3DMS, and Model muse was used. The standard advection-dispersion-reaction model (Harbaugh and McDonald, 1996; Butler et al., 2003; Templeton et al., 2015) as outlined below was adopted:

$$\frac{\partial C}{\partial t} = \frac{d_L v}{R} \frac{\partial^2 C}{\partial z^2} + \frac{v}{R} \frac{\partial C}{\partial z} - \frac{\lambda}{R} C \quad \dots\dots\dots (1)$$

Where;

C = the concentration of chloride in unsaturated geological material (g/m³) (which is equivalent to [mg/L]),

d_L = the longitudinal dispersivity (m),

v = the mean pore water velocity (m/day),

R = the retardation coefficient (> 1 where sorption present),

λ = the linear decay coefficient (1/day), which is related to the half-life by $T_{1/2} = \log(2)/\lambda$ (days).

For unchanging conditions, with a chloride concentration at the bottom of the pit latrine of C_0 , then the concentration C_{pw} at a depth z_w , the depth of the water table below the base of the pit, is given as:

$$C_{pw} = \frac{C_0}{2} \left[\frac{(\exp(vz_w)(1-\gamma))}{2vd_L} \operatorname{erfc}\left(\frac{z_w - v\gamma t}{2\sqrt{vd_L t}}\right) + \frac{(\exp(vz_w)(1+\gamma))}{2vd_L} \operatorname{erfc}\left(\frac{z_w + v\gamma t}{2\sqrt{vd_L t}}\right) \right] \dots\dots\dots (2)$$

Where:

$$\gamma = \sqrt{1 + \frac{4\lambda d_L}{v}} \dots\dots\dots (3)$$

The solution was implemented in MODFLOW/MT3DMS. In this regard, water flow balance and chloride mass balance were modelled to estimate the dilution of the chloride in the aquifer of the area and the resultant total concentration in the aquifer (C_{ao}) after different elapsed times 1825 days ($1.577e+8$) to 7300 days ($6.307e+8$) i.e. 5-20 years from present.

Water flow balance: $Q_{ao} = Q_{ai} + A_r \cdot q_r + A_p \cdot q_p \dots\dots\dots (4)$

Chloride mass balance: $Q_{ao} \cdot C_{ao} = Q_{ai} \cdot C_{ai} + A_r \cdot q_r \cdot C_r + A_p \cdot q_p \cdot C_{pw}$... (5)

$$Q_{ai} = W \cdot H \cdot K \cdot i_i \dots\dots\dots (6)$$

Where:

Q_{ai} = inflow into the aquifer (m³/day),

Q_{ao} = outflow of the aquifer (m³/day),

C_{pw} = chloride concentration reaching the top of the water table (obtained from the advection-dispersion-reaction model, in g/m³),

C_{ao} = chloride concentration in the aquifer outflow

C_{ai} = chloride concentration in the aquifer inflow (assumed to be 0),

C_r = chloride concentration from surface runoff (assumed to be 0),

q_p = water flux from the pit latrine (0.002 m/d),

q_r = groundwater recharge rate (m³/m²/day),

A_p = total surface area of the pit latrines (m²),

A_r = surface area of aquifer recharge (m²),

W = width of the aquifer (m),

H = height of the aquifer (m),

K = hydraulic conductivity (m/d) and

i_i = hydraulic head gradient.

The above mentioned are represented in Figure 6.2 below;

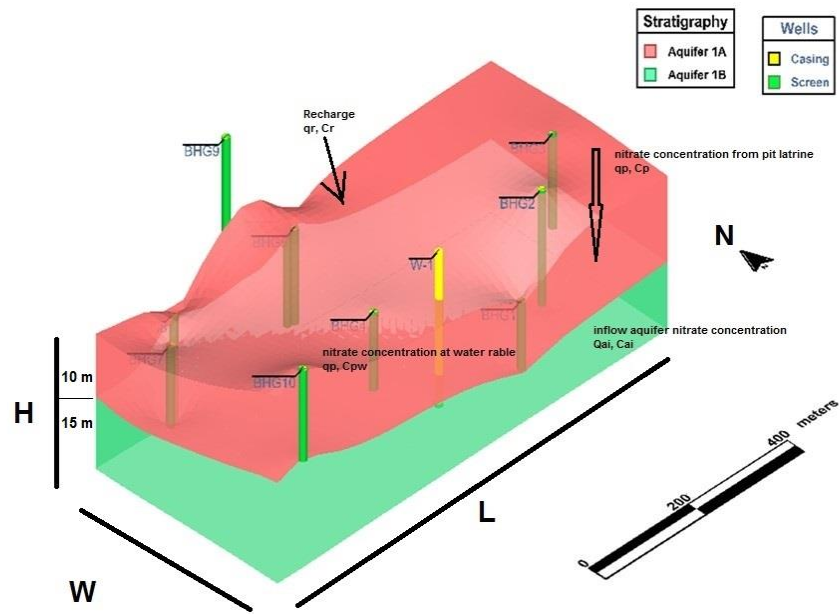


Figure 6.2 Schematic descriptions of the imputed model parameters in the study area

A range of chloride concentration was observed based on the advection-dispersion-reaction model. Chloride half-life of 190,000 days was used to capture the range of C_{pw} values entering the aquifer at the depth of 10 m (Figure 6.2). This value is the mean life time generally used to describe the exponential decay of chloride in geological environment. The result of the simulation for the different periods and their outcomes were summarised in Table 6.1. A range of chloride concentration was observed based on the advection-dispersion-reaction model (Figure 2). The result of the simulation for the different periods shows that chloride concentration will reach 37 mg/l and 42 mg/l in the years 2021 and 2026 respectively. Also, within the modelled domain, a chloride concentration of 80mg/l will be attained in 2031.

Table 6.1 Summary of model simulation results and key outcomes

Model parameters	Values	Outcome (Cpw predicted)
<u>Scenario 1</u>		
Stress period (days)	1.577e+8	Chloride concentration in the upper aquifer reaches about 40 mg/l by the year 2021
i_i (m/day)	0.01	
q_r (m ³ /m ²)	0.0001	
<u>Scenario 2</u>		
Stress period (days)	3.154e+8	Chloride concentration in the aquifer reaches 80 mg/l in the year 2026
i_i (m/day)	0.01	
q_r (m ³ /m ²)	0.0001	
<u>Scenario 3</u>		
Stress period (days)	4.173e+8	Chloride concentration in the upper aquifer ranges up to 100 mg/l in 2031
i_i (m/day)	0.1	
q_r (m ³ /m ²)	0.0001	
<u>Scenario 4</u>		
Stress period (days)	6.307e+8	Chloride concentration in the modelled aquifer reaches about 300 mg/l by 2046
i_i (m/day)	0.1	
q_r (m ³ /m ²)	0.0001	

Equally, a gradual increase in the concentration of chloride was observed during this period. Furthermore, the concentration of chloride within the upper aquifer will reach up to 100 mg/l in 2036. Lastly, the model show that chloride concentration in the upper aquifer will reach up to 300 mg/l by the end of 2066, thereby exceeding the maximum tolerable limits (250 mg/l) outlined by the WHO (2011). This trend is likely going to be aggravated by population growth in the study area.

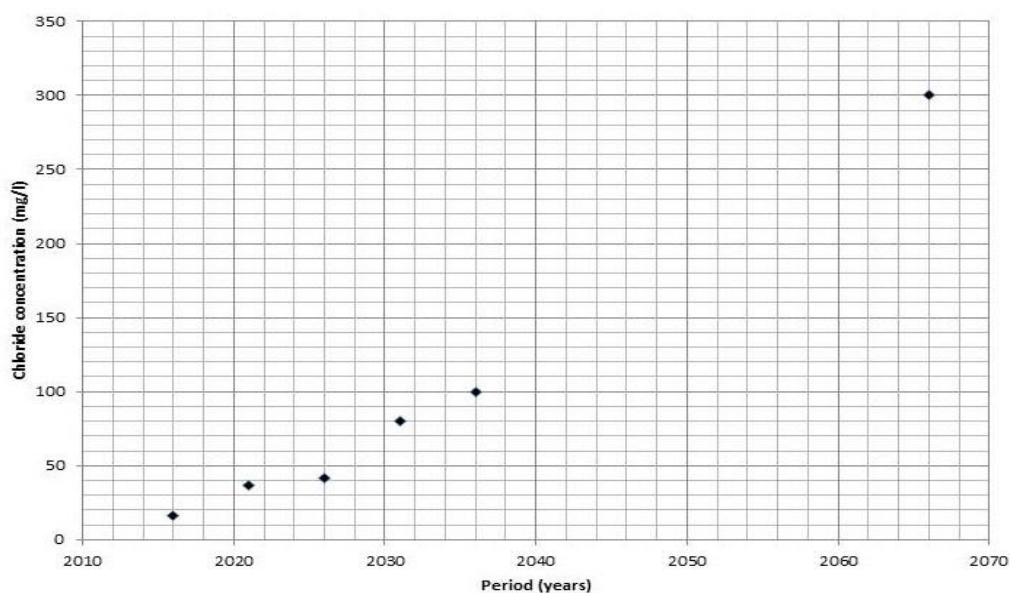


Figure 6.3 range of chloride concentration over different periods

Thus, based on the results presented above, the guidelines for protecting the groundwater system in the study area will be developed in the next chapter (chapter 9). This will mitigate the impact of pit latrines on groundwater resources of the study area. Despite the significance of the result of this modelling, it is noteworthy that model results can never represent the natural system they represent. This is primarily attributed to the predictive improbability of the modelling. Notwithstanding, it is worthy to stress that the result of the prediction could be used to inform decision provided that appropriate monitoring is put in place so that predicted results can be checked. However, limitation exists as the predicted results are not checked in this study due to constraints in resources. Therefore, further studies can take advantage of this limitation.

6.2 Follow-up (household) survey data used for developing the new guidelines

The results of the survey (Table 6.2) below show that there is significant variation in the depth of pit latrines among the various households surveyed. In this regard, majority of the households (23.9%) have their pit latrines reaching the depth of 6 metres (Figure 6.4). Also, about 22.8% and 20.8% of the households surveyed have their pit latrine depths in the range of 5 and 4 metres respectively. Others pit latrine depths include 3 metres (12.7%), 2 metres (13.2%), and 1 metre (4.1%).

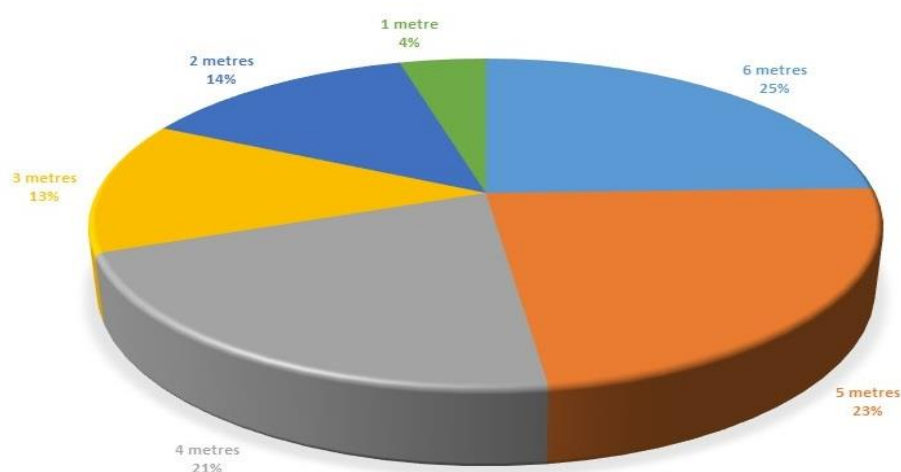


Figure 6.4 Percentage distributions of different pit latrine depths in the case study area

Table 6.2 Summary of household survey data (n=196)

Parameter	Average	Maximum	Minimum
Depth of pit latrine (metres)	4.92±9.54	6	1
Distance between pit latrine & water point (metres)	7.77±12.34	167	1
Distance between dumpsite and water point (metres)	73.8±77.6	800	10

Likewise, the distance between the pit latrines and the household's water supply points varied significantly as summarised in Table 6.2 above. In this respect, majority of the households (13.7%) fall within the range of 9 metres as the distance between their pit latrines and water supply points. Also, about 10.7% and 10.2% of the households have 2 and 8 metres as the maximum distance between their onsite sanitation system and water points. Others are 7 metres (9.6%), 3 metres (6.6%), and lastly the maximum distance recorded was 167 metres (0.5%).

Furthermore, the distance between the households and the dumpsites were also determined. In this regard, varying distances were observed as summarised in Table 6.2 above. The result show that majority of the households (12.2%) are within 50 metres distance. Two households have the distance of about 800 and 500 metres respectively. Also, about 1% and 2% of the households are within 300 and 200 metres limits respectively. Those within the moderate distance category include 55 metres (5.1%), 60 metres (8.1%), 65 metres (2.1%), 70 metres (4.6%), 80 metres (3.0%), and 90 metres (4.1%). The households within the short distance category

include 10 metres (0.5%), 15 metres (2.0%), 20 metres (3.0%), 25 metres (3.6%), 30 metres (7.1%), 35 metres (4.1%), 40 metres (6.6%), and 45 metres (8.6%).

Lastly, the survey result on the number of persons using the pit latrines daily indicates that pit latrine with 1-10 persons per day constitutes about 35%, those in the category of 11-20 persons per day make up about 55%, and those with more than 20 persons per day constitutes the remaining 10%. The average number of persons (users) per pit latrine per day is 15 people.

6.3 Establishing Sustainable Guidelines for Unconsolidated Sediment Hydrogeological Environment

In developing the guidelines for mitigating the impact of pit latrines on groundwater, this section integrates the outcomes of the stakeholder engagement chapter (chapter 5), the modelling of chloride contamination presented in this chapter (see section 6.1), and the follow up survey results presented in Table 6.2. The results of the modelling shows that at the depth of 10 metres, the potentials for chloride contamination of the upper aquifer is evident. Accordingly, in the next 30 years, chloride concentration in this aquifer will reach 300 mg/l. Thus, this information is vital for the establishment of the guidelines for mitigating the impact of pit latrine on groundwater in the study area. This type of sedimentary environment is the most dominant and widespread hydrogeological environment in most parts of the Sudano-sahel belt of West Africa. The guidelines can be used by the various stakeholder groups in the region to protect the integrity of the underlying aquifers.

Table 6.3 Summary of key outcomes of foregoing chapters used in developing the new guidelines

Chapter	Key outcomes/ findings	Justification for using the outcomes in this section
Chapter 5	<ul style="list-style-type: none"> • Identifies different stakeholder groups • Engages the different stakeholders groups in groundwater management decision making • Outlines the different views and opinions of the stakeholders engaged 	The identified stakeholder groups will be assigned key roles in the management, maintenance and construction of onsite sanitation systems (Table 6.6).
This chapter (section 6.1)	<ul style="list-style-type: none"> • Chloride modelling shows potentials for groundwater contamination of the shallow aquifer in different time scales • Chloride concentration will reach 300 mg/l in the next three decades 	This information will be useful in developing the new guidelines; this is crucial for determining the overall desired mitigation framework
This chapter (section 6.2)	<ul style="list-style-type: none"> • Reveals the different households pit latrine depths • Estimates average number of pit latrine users per day 	This outcome is useful for benchmarking the tolerable pit latrine depths in avoiding potential contamination effects (Table 6.4).

Furthermore, secondary data were obtained from published papers and other grey literatures for the purpose of comparing the new guidelines to globally accepted standards. Also, the justification for the development of these guidelines by the study was necessitated by the inadequacy of existing frameworks to mitigate the impact of pit latrines on the groundwater system in the sub-region. Thus, this chapter identifies a window of opportunity where sustainable guidelines aimed at protecting the

underlying aquifers can be developed and implemented locally, and across the sub-region.

Additionally, these guidelines can complement those developed by the World Bank and the UNDP; as mitigation framework for open dumpsites are not provided currently. Therefore, adherence to the activities described in this study (Tables 6.4, 6.5, 6.6, and 6.7) will assist in achieving the overall aim of the study. The figure below (Figure 6.5) explains the steps taken to develop the guidelines and the activities involved in the different phases of the guideline development. Detailed information on the development of the guidelines is outlined in the methodology chapter (see sub-section 4.4).

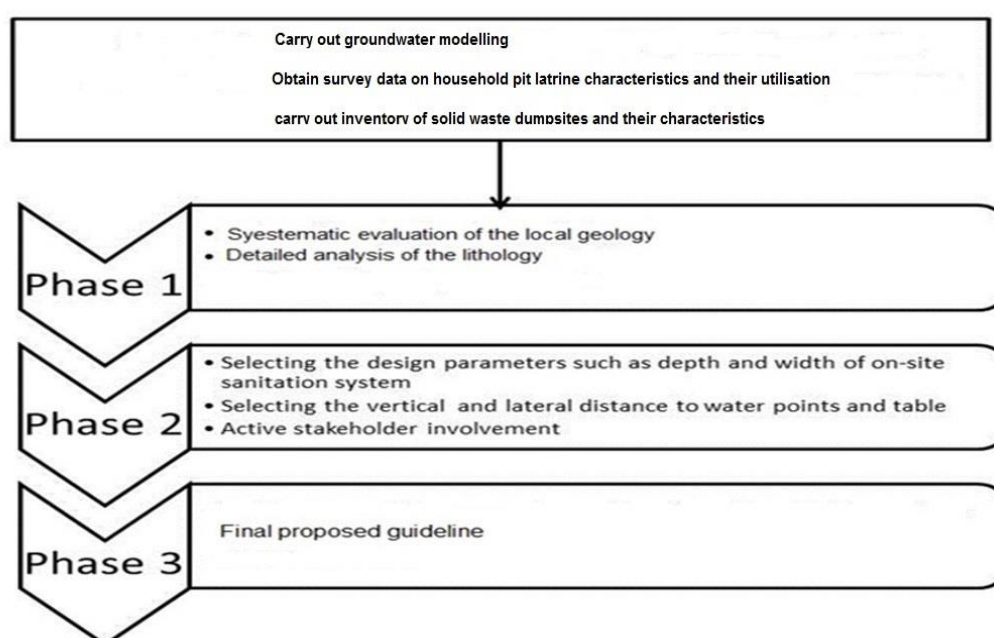


Figure 6.5 Steps for developing the guidelines for mitigating the impact of on-site sanitation systems in groundwater

6.3.1 Mitigation Framework for Unconsolidated Sediment Hydrogeological Environment

As previously evaluated in chapter 5, unconsolidated sediments consisting of gravel, coarse sand, siltstone and clay (2mm to $<2\mu\text{m}$) dominate the hydrogeological environment of the study area. Also, the modelling output indicates that chloride concentration of about 300 mg/l will be recorded in the next three decades in the study area. Thus, this chapter outlines different phases for the construction of pit latrines in the unconsolidated sediments of the study area. The first phase is regarded as the investigation phase, the second, and the third phase is considered operation and maintenance phases respectively.

Taking the abovementioned into consideration, when citing a pit latrine in unconsolidated sedimentary environment, firstly, it is important to carry out systematic lithological/ sediment sampling at varying interval (vertical and horizontal) to ascertain the type and distribution of the sedimentary materials. This will allow the conceptualisation of the hydrogeological environment and the prediction of the resultant processes occurring in the subsurface.

The second phase is the design and construction phase. This is the most important stage at which sustainable design parameters for the construction of pit latrines and open dumpsites are selected. Taking the surveyed households pit latrines shows that most of the households have deep pit latrines (up to 6 metres). Thus, taking the output of the modelling as a decision support tool, the study recommends that the

depth of the pit should not exceed 3 meters. This is because the modelling indicates the potentials of chloride contamination of the local aquifer at the depth of 10 metres. Also, the vertical distance between the pit and water table should be at least 10 meters in gravels and sandstones, 5-6 meters in siltstones and clays, and the lateral distance between the pit and borehole (water well) should correspond to 10-15 meters for gravels and sandstones (up-gradient) and 25-30 meters (down gradient) (Table 6.4). Comparison of the design parameters of this study were carried with other studies (similar sites) and internationally standards (Table 6.5). The design parameters for open dumpsites are; depth of dumpsite pit 0.5-1 meter, vertical distance between bottom of dumpsite and water table should be at least 5 meters for all unconsolidated materials, and lateral distance to water source should be at the minimum of 10 and 15 meters for up-down gradients respectively (Figure 6.6).

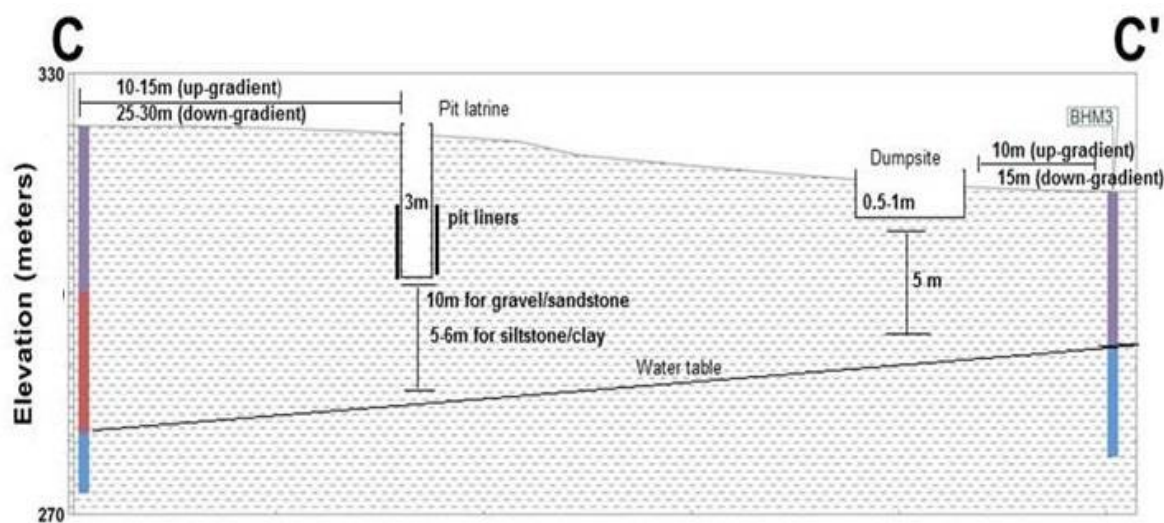


Figure 6.6 Conceptual models for mitigating anthropogenic impact in unconsolidated sediments

Likewise, for unconsolidated materials with high porosity and permeability (coarse sandstone), both pit latrines and dumpsites should be properly lined. In each case,

there is a need to create enough space for the emptying of the contents of the pit latrines and dumpsites when they are full to their capacities.

The third phase is the operation and maintenance phase; this is a very vital stage for ensuring the sustainability of the on-site sanitation systems. Efficient use of pit latrines and dumpsites are recommended. When the contents of the pit latrine is full, it is recommended that the sludge should be collected and mixed with other organic wastes (composting) for beneficial use by local farmers. This will discourage the use of chemical fertilisers, and it will provide job opportunities. Also, it is vital to develop simple communal rules that will ensure the sustainable operation and maintenance of these systems. The relevant stakeholders identified in chapter 4 (see section 4.2.1) can be engaged to carry out the functions summarised in Table 6.4.

Table 6.4 Best management guidelines for unconsolidated sediments

Phases	Best management practices
Phase I (Exploration stage)	<ul style="list-style-type: none"> • Carry out systematic lithological sampling & investigation • Carry out geophysical/geotechnical investigation to determine the depth to the water table & groundwater flow direction • Ensure local stakeholder participation in investigations
Phase II (Design and construction)	<ul style="list-style-type: none"> • Total depth of the pit should not exceed 3 meters • The vertical distance between the pit and water table should be at least 10 meters in gravels and sandstones • Vertical distance between pit and water table should be between 5-6 meters in siltstones and clays • The lateral distance between the pit and borehole (water well) should correspond to 10-15 meters for gravels and sandstones (up-gradient)

and 25-30 meters (down-gradient)

- For dumpsites, depth of the pit should vary between 0.5-1 meter depending on local condition
- Vertical distance between the bottom of dumpsite and water table should be at least 5 meters for all unconsolidated materials
- Lateral distance to water source should be at the minimum of 10 and 15 meters for up-down gradients respectively.
- Consideration of adequate spacing for emptying purposes
- Accommodate stakeholder inputs and suggestions in design

Phase III (Operation and maintenance)

- Efficient use of pit latrines and dumpsites in a sustainable way
 - Educate & engage local stakeholders in operation and maintenance
 - Develop local communal rules to guide operation & maintenance activities
 - Carry out periodic water quality monitoring exercise
 - Routine addition (at least monthly) of other organic wastes to enhance decomposition of faecal matter
 - Sealing of pit covers to enhance denitrification.
 - When the contents of the pit latrine is full, it is recommended that the sludge is collected and mixed with other organic wastes (composting) for beneficial use by local farmers.
-

Table 6.5 Comparison of the design parameters developed by this study to established standards

Guidelines (study)	Pit bottom distance to water table	Lateral distance to water point	Depth of pit (latrines)	Width of pit (latrines)	Dumpsite bottom distance to water table	Depth of pit (dumpsites)	Width of pit (dumpsites)
UNDP/ World Bank (2010)	2 metres	25-30 metres	2 metres	1.5 metres	N/A	N/A	N/A
UNICEF (2009)	3 metres	30-50 metres	Approx. 1.50 metres	1.50 metres	N/A	N/A	N/A
USAID (2010)	2 metres	20 metres	2.1 metres	1.50 metres	N/A	N/A	N/A
Cavana (2011)	2 metres	30 metres	2 metres	1-1.2 metres	N/A	N/A	N/A
WASH-LIBERIA (2009)	2-3 metres	25-30 metres	2 metres	1 metre	N/A	N/A	N/A
This study	5-6 metres	25-30 metres	3 metres	1-1.50 metres	5 metres	1-2 metres	1 metre

6.4 Guidelines for the Maintenance and Operation of Existing On-site Sanitation Systems

Formal guideline on the operation and maintenance of existing on-site sanitation systems (pit latrines and dumpsites) in the case study area is non-existent. This situation if not addressed will continue to put enormous pressure on the shallow groundwater system. In order to develop practical guidelines that will be implemented by the various stakeholders groups engaged (chapter 5). Below, the operation and maintenance guidelines are outlined:

6.4.1 Operation and Maintenance Guidelines for Existing Pit latrines

The utilisation and safe disposal of the contents of pit latrines will stop the spread of transmissible diseases. Local authorities and communities need to consider the following guidelines in ensuring effective use and disposal of human wastes which in turn brings about enormous healthiness of the communities. Also, the control and management of these human wastes is saddled on the local stakeholders whom will be involved in the preventive and maintenance activities for pit latrine waste disposal.

The creation of awareness among the primary stakeholders, and their direct involvement in addressing sanitation problems can individually aid behavioural change in communities, and will improve the operation and maintenance of pit latrines and other on-site sanitation systems. The group of youths and women engaged in chapter 6 will have a key role to play here.

Major operation activities for pit latrines consist of frequently cleaning the floor of the latrine with water (and antiseptic) to remove any spilled urine or excreta. This practice can be carried out at the household levels. The local residents have key roles to play in ensuring the sustainability of the system. Table 6.6 summarises the major operation and maintenance guidelines for existing (already developed) pit latrines, the category of stakeholders involved and their roles, and the required expertise.

Table 6.6 Proposed guidelines for mitigating impact of existing pit latrines and the stakeholders involved

Stakeholders	Roles	Operation & maintenance activity	Requisite expertise
Residents, youth and women groups	Pit latrine users	Close the pit cover	✓
			✓
		keeping the latrine clean	✓
		Inspecting and carrying out inventory of existing latrines	
Local authorities, officials of the ministries of environment and health, community leaders, representatives of water user, youth and women groups, CSOs, NGOs	Inspection of environmental & sanitary conditions	Routine monitoring sanitary conditions of latrines	✓
		Inspection and assessment of local water supply sources	✓
		Educating residents on hygienic behaviour	✓
State and local authorities, residents, CSOs, NGOs, professional organisations and	Design, building and repair works of latrines	Provision of sustainable designs for upgrading existing latrines	†

research institutions		Routine repair and maintenance of existing latrines	†
		Awareness creation on adoption of new designs	√
State and local authorities, local businesses, residents, youth groups, officials of the ministries of water, environment and health	Facilitate small-scale enterprises participation in latrine emptying activities	Investment, provision of loans, and enabling business environment for local businesses	£
	Effective emptying of pit latrines	Provide training on effective emptying technologies	†
		Subsidising costs of emptying operations	£
	Latrine contents and sludge management	Providing employment opportunities for youths in latrine emptying technologies and sludge management	£ √
State and local authorities, farmers & youth groups, NGOs, CSOs, and Community leaders	Adoption and implementation of policies that discourages the use of chemical fertilisers	Providing incentives to farmers that use organic fertilisers	£ √
	Adoption and implementation of policies that enables the use of composted or organic fertilisers	Establish small scale composting plants in communities and compost pit contents for use by local farmers	† £

√ Simple (training activities, capacity building, gender sensitive awareness-creation);
† technical skills; £ financial capability

6.4.2 Operation and maintenance guidelines for existing open dumpsites

Similarly, open dumpsites are also important sources of anthropogenic contamination in the case study area. They are generally found across the study area near residential areas and local markets. The poor state of waste management in these dumpsites is largely attributed to the rapid population growth and uncontrolled-urbanisation, low-level of financial investments and weak enforcement of environmental regulations by the state and local authorities. Thus, the impact of existing open dumpsites if unabated will further exert pressure on the shallow groundwater resources. Table 6.7 summarises the proposed guidelines for mitigating the impacts of existing open dumpsites.

Table 6.7 Proposed guidelines for mitigating impacts of existing dump sites and the stakeholders involved

Stakeholders	Roles	Operation & maintenance activity	Requisite expertise
State and local authorities, community leaders, residents, water user groups, NGOs, CSOs	Environmental community association	Provision and enforcement of common rules on incessant waste disposal	✓
	Provision of stringent Legislation and their enforcement	Review and implement laws on environmental protection	✓
	Sensitisation of communities on the implications of incessant waste disposal	Gender-sensitive awareness and education campaign on environmental protection	✓
Residents, NGOs, CSOs, and all water user groups	Beneficiaries and dump site users	Adoption of effective waste management & disposal in dumpsites	✓
State and local authorities, government agencies, water user groups, CSOs and NGOs	Inspection of environmental & sanitary conditions	Mobilisation and coordination of environmental vigilance activities	✓
		Routine monitoring of dumpsites	
		Inspection and assessment of dumpsites sanitary conditions	✓†
State and local authorities	Provision of incentives and welfares	Educating residents on effective waste management strategies	✓
		Development of suitable local household waste incentive scheme (food-for-waste, waste-for-money programmes etc.)	£

✓ Simple (training activities, capacity building, gender sensitive awareness-creation); † technical skills; £ financial capability

6.5 Discussions

This section presents the discussions on the aspects of chloride contamination modelling due to the impact of pit latrine and the socio-technical aspects of the new guidelines developed herein.

6.5.1 Chloride modelling

The ever increasing uses of both pit latrines and groundwater resources in Maiduguri causes concerns that pit latrines may ultimately cause human and ecological health impacts associated with microbiological and chemical contamination of groundwater. Safe human excreta disposal is a vital component of environmental sanitation. In both developing and developed countries of the world, proper excreta disposal is amongst the most persistent public health problems. Concern about groundwater contamination due to the impact of on-site sanitation system relates principally to unconfined and, to some extent semi-confined aquifers. On-site sanitation systems can have an adverse effect on underlying aquifers, because faecal matter accumulates in-situ and leaching of contaminants into the geosystem may possibly occur.

In the study area, pit latrines are the most common forms of onsite sanitation facilities. In most cases they are regarded as the suitable means of disposing human wastes, however, the excessive use and proliferation of onsite sanitation system greatly raises concern about contamination of groundwater. A lot of this problem

arises in rural areas, and in densely populated peri-urban areas where local, shallower, and often untreated, groundwater sources are used. In such conditions, microbial contamination is possibly as a result of poor well design and/or construction. In recent years, this situation has caused increased nitrate and chloride concentrations in the underlying aquifers of Dhaka, Greater Buenos Aires, Lagos, and Nairobi (World Bank, 2002). Therefore, the use of onsite systems is not recommended unless the water table is extremely low and sediment conditions are not likely to contribute to susceptibility of groundwater pollution.

Noteworthy, the analyses presented in this chapter depicts chloride as an important indicator parameter of faecal contamination rather than toxic contaminant with greatest health effects on humans. Chloride concentration in groundwater is commonly investigated due to its high concentrations in human excreta and its relative mobility in the geosystem. It is characteristically transported in the subsurface with minimal retention during groundwater flow, and chloride concentrations are tracked with nitrate levels (Banks et al., 2002; Ahmed et al., 2002).

Similarly, nitrate and ammonia are among the most important parameters used in determining groundwater contamination due to the influence of pit latrine. They are widely investigated due to their health risks (WHO 2006). Both nitrate and ammonia are derived directly or indirectly from latrine wastes, organic wastes, fertilizers and farm animal operations. Their concentrations in shallow aquifers in sub-Saharan Africa are reported by some authors (Ndambuki et al., 2012; Graham et al., 2013;

and Templeton et al., 2015). Different technologies for reducing the impact of nitrate and ammonia exist.

Technologies such as permeable reactive barrier, phytoremediation, ion exchange processes will help to reduce the concentration of these contaminants to tolerably safe limits. However, these engineered solutions alone cannot address the situation. They need to be integrated with non-engineering solutions; such as preventative measures of best management practices in a holistic fashion. It is worth mentioning that these technologies are often expensive in nature and are difficult to implement, especially at the household and community levels in resource scarce countries. Hence, the need to develop a local strategy contained herein the study.

Equally, the advances in technology and their practical application may greatly reduce the microbial and chemical threats to underlying aquifers. However, despite the advances, it is still unclear whether these options are economically viable and culturally acceptable to people in low-income countries (Dzwairo et al., 2006). Due to this reason, the study proffers a pragmatic (socio-technical) methodology that is simple and straight forward to implement at the different levels of pit latrines design, construction, and management in the study area. This methodology will mitigate the impact of onsite sanitation systems on groundwater in sub-Saharan Africa.

As the contaminants are released from their sources, the unsaturated zone above the aquifer acts as buffer that reduces pollution effects of aquifers. The local geology

of the study area has demonstrated the ability to remove faecal microorganism and chemical compounds by retarding their movement towards the saturated zone. Thus, rock types and the degree of consolidation of sediments are key factors to consider in assessing the vulnerability of an aquifer to pollution in a particular area. Furthermore, within the saturated zone, dispersion and dilution play an important role in reducing the concentration of the contaminants dissolved in the groundwater.

The thick Chad Formation (alluvium cover) acts like a natural filter; it has the potentials to impede the movement of the invading contaminants. The physical and chemical characteristics of the sand and silt-stones aid ion exchange processes within the local geological environment. In this respect, the alkali metals derived from the primary minerals react with the various anions and cations derived from the above ground anthropogenic sources. Equally, in this type of geological environment, most inorganic contaminants are adsorbed to the surfaces of the larger sediment particles while the organic contaminants are adsorbed to the surfaces of the secondary mineral particles.

Therefore, in view of the local geology of the study area, the development and application of an integrated approach; that combines both technical (review of design and construction parameters) and social dimensions (stakeholder inclusions and defining their stakes) will address the situation. Others are systematic lithological and hydrogeological mapping in determining the depth to the water table, investigating the geological material characteristics prior to installing on-site systems.

Furthermore, given the siting standards for latrine construction, it is important to re-evaluate the vertical and lateral separation between the groundwater supply source and the pit latrines. This is because different hydrogeological environments require different strategies in addressing local problems. A limited number of field studies (World Bank, 2002; Graham et al., 2013) have shown that a lateral and vertical separation distance of about 10 and 2-4 metres respectively between the source and the receptor is sufficient enough to reduce the concentrations of faecal indicator contaminants to the minimum levels.

Therefore, balancing the risks of onsite sanitation systems and their potentials for impacting groundwater resources negatively is fundamental in the study area. Therefore, more efforts are needed to develop sustainable and more robust approaches to siting pit latrines. Sustainable guidelines should be developed and tested empirically to ensure protection of groundwater quality after their implementation under local conditions.

Chloride concentration is one of the best ways of measuring the effectiveness of the existing operational frameworks for pit latrines design, management, and operation. The assessment of chloride concentration in groundwater due to the impact of pit latrine is best carried out by predicting their future concentrations. This can be carried out with different modelling techniques. The MODFLOW codes developed by

the United States Geological Survey (USGS) is one of the best modelling tools that performs this function (USGS, 2000), .

The modelling carried out in this study shows that the depth of the upper aquifer of the study area ranged between 15 and 25 metres. This implies that the local aquifer is not likely to be impacted negatively by the existing onsite systems in the study area. Theoretically, the chances of contamination increases significantly in geological settings where the water table is shallow (1m-10m). The output of the modelling indicates that the hydraulic heads and recharge rates are having significant influence on the amount of predicted chloride concentrations in the boreholes of the study area.

The result of groundwater modelling can be used by the local water managers and other relevant stakeholders who need to make informed decision on groundwater management (Rushton and Skinner, 2012). In the study area, the interplay between the density of pit latrines and booming population will further increase chloride concentration in the groundwater.

Despite the low adverse health effects by chloride, when they react with sodium found in the natural environment, they will form salts. Groundwater with concentrations of chloride in excess of 230 mg/l that discharges to surface water may cause toxic effects to aquatic life (USEPA, 2002). However, too much intake of

sodium chloride salt is a major known risk factor for hypertension or high blood pressure (USGS, 2000).

In addressing this problem, there are a wide range of mitigation frameworks that can be adopted in the short-medium-and long terms that will provide solutions to the perceived risks posed by pit latrines on the underlying aquifers. Mitigation frameworks such as keeping the pit well above the water table, well head protection, standard design and construction parameters were suggested by various authors (Almasri, 2007; Tredoux et al., 2000; Templeton et al., 2015).

In view of the above, site-specific analyses of safe sanitation options suitable for developing countries have been outlined by the British Geological Survey (BGS) (Lawrence et al. 2001). The BGS guidelines provide a set of rules for determining the optimum horizontal separation between sanitation facilities and drinking-water sources for a variety of geological environments. These guidelines have been tested in Bangladesh (Ahmed et al. 2002), Uganda (Howard et al. 2003), and Argentina (Blarasin et al. 2002) and have been advocated as sensible practice for aquifers limited measured data.

The possibilities for extensive groundwater contamination from the influence of onsite sanitation systems can be controlled by factors such as design and construction technology, operation and maintenance, and other social factors such as sustainable use. Also, pit latrine depth, presence of liners, and the quality of

construction can greatly influence contaminant leaching and containment (Graham et al., 2013).

Lastly, the problems of the existing on-site sanitation systems can be addressed by involving all the relevant stakeholders in addressing the situation. This can be achieved by providing simple training activities, capacity building, and gender sensitive awareness-creation for the primary stakeholders (local residents). While the state and local authorities and other strategic stakeholders' needs to focus on the aspects of technical and financial capacities. Also, the local council and the relevant state agencies needs to carry out a comprehensive inventory of the households with pit latrine depth ranging between 6-10 metres (Table 6.2). This will help in the comprehensive assessment of the likely treats to groundwater. Short term solutions of emptying the contents of the existing pit latrines in the households affected and the provision of subsidy to them by the government in constructing improved pits will be vital.

6.5.2 Follow-up survey and new guidelines development

Considering the results obtained from the household survey, an average pit latrine depth of 4.92 metres and maximum depth of 6 metres were obtained across the various households. This suggests that most households have overlooked the implications of greater pit latrine depths on groundwater quality. Most likely the households believe that the greater the depth, the longer the time it takes to fill. Also, an average distance of 7.77 metres was recorded between pit latrines and water

points. This result is at variance with the recommended World Bank/UNDP/UNICEF guidelines between pit latrines and water points. The shorter distances between dumpsites and water points across the various households obtained in the case study area may be ascribed to the poor sanitary practices of the local communities.

Thus, there is the need for adequate and proper awareness campaign programme in the area. Also, it is worthy to note that short lateral distance between onsite sanitation systems and water points in many parts of sub-Saharan Africa and the poor sanitary practices such as open defecation by individuals as well as the dumping of wastes near water supply points may lead to contamination and its associated water- borne diseases.

Although, the guidelines developed by the World Bank, UNDP, and UNICEF are aimed at mitigating the impact of onsite systems on groundwater. Such criteria may not be suitable for all localities due to the differences in natural geological conditions and this may not guarantee total groundwater protection. Therefore, the guidelines developed by this study can be suitable for the case study area and other similar sites across the region. Likewise, they can be integrated with the existing guidelines in ensuring sustainable groundwater protection.

In view of the above, the guidelines proposed in this chapter are an important step towards ensuring the sustainable management of groundwater resources in sub-Saharan Africa region. This is because unconsolidated sediments (sandstones,

siltstones, and clays) serves as an important hydrogeological environment; that directly supply water for about 70-100 million people mostly rural dwellers in sub-Saharan Africa.

The possibilities for extensive groundwater contamination from the above ground anthropogenic activities (pit latrines and open dumpsites) can be controlled by factors such design and construction technology, operation and maintenance, and other social factors such as sustainable use. Also, pit latrine depth, presence of liners, and the quality of construction can greatly influence contaminant leaching and containment. This view was also expressed by Graham et al. (2013) in his assessment of pit latrine design criteria.

Lastly, the problems of the existing on-site sanitation systems can be addressed by involving all the relevant stakeholders in addressing the situation. This can be achieved by providing simple training activities, capacity building, and gender sensitive awareness-creation for the primary stakeholders. While the state and local authorities and other strategic stakeholders should focus on the aspects of technical and financial capacities. Also, the local council and the relevant state agencies need to carry out a comprehensive inventory of the households with pit latrine depth ranging between 4-6 metres. This will help in the comprehensive assessment of the likely threats to groundwater. Short-term solutions of emptying the contents of the deep pit latrines in the households affected and the provision of subsidy to them by the government in constructing shallow pits will be vital.

6.6 Summary and conclusion

The first part of the chapter modelled the concentration of chloride in the groundwater across different time scales. Making the best case assumptions, the modelled aquifer as analysed in this chapter is currently safe for consumption and other domestic use. However, the tolerable limits of chloride concentration (250mg/l) are likely to be exceeded in the next three decades (30 years). This can be greatly influenced by demographic factors in the study area.

However, recommendations for mitigating groundwater impacts can be both qualitative and quantitative. Many countries across sub-Saharan Africa are already having developmental challenges attributed to poor infrastructure. Therefore, an alternative guideline for the mitigation of the impact of onsite sanitation system is important in the study area.

The second part of the chapter reveals that both vertical depth and horizontal spacing play significant role in mitigating the impact of onsite sanitation systems on groundwater aquifers. It discloses that shorter vertical depths and longer lateral separation between the onsite sanitation systems and water table as well as supply points will significantly reduce the risk of chloride contamination of underlying water resources.

The dependence on groundwater as a primary water supply source is increasing in sub-Saharan Africa region. Equally, the provision of unsustainable sanitation facilities threatens the available groundwater resources. Accordingly, there is the need to understand how pit latrines and open dumpsites affect available groundwater in the various hydrogeological environments and develop guidelines for their protection. Therefore, careful siting of pit latrines and the adoption appropriate local technology and the management of existing onsite sanitation systems will go a long way in addressing the situation.

Also, the second part of this chapter has developed a realistic and sustainable guideline that will mitigate the impact of pit latrines on the groundwater of the study area. In general, unconsolidated sedimentary environments (sandstone, siltstone, and clay) have the highest attenuation capacities of contaminants. However, it is worthy to note that there are multitudes of guidelines and design criteria developed by World Bank joint programmes across the globe, but gap exists in developing suitable guidelines for mitigating the impact of dumpsites as offered by this study.

Lastly, this chapter has investigated the concentration of chloride in the groundwater of the study area in assessing the impacts of pit latrine, the chapter stresses that the involvement of the local stakeholders in the design, operation, and maintenance of the onsite sanitation systems will ensure sustainability and the achievement of sustainable groundwater management. It concludes that the implementation of the appropriate guidelines for the management of existing on-site sanitation systems will

protect the integrity of the underlying aquifer. The next chapter presents the conclusions, policy and future studies recommendations respectively.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORK

7. Introduction

In this concluding chapter, it is imperative to review and discuss the overall research undertakings reported in the thesis; in order to ascertain whether or not the research objectives and questions guiding the study have been addressed adequately. Therefore, the objective of this chapter is to present the conclusion on all the key findings of the study and provide recommendation for future work.

7.1 Conclusions

This PhD research was set out to develop a sustainable groundwater management strategy to be implemented in the Nigerian sector of the Chad Basin. This study has found out that stakeholder exclusion in the management of groundwater is a key feature of the current system. The study has identified and engaged the various stakeholder groups (including women groups). As a practical consequence, the study carried out a local capacity building and enhancement workshops for the primary water users with low capacities. This has built local institution for groundwater management in the study area and enhanced communication between the different stakeholder groups. The stakeholder participation has generated real benefits, fostered cooperation in developing the alternative guidelines. Hence, there is the need for greater participation by all the stakeholders.

Consequently, the study used realistic evaluation to show that the current approaches to groundwater management in the case study area are not making the desired impact. Based on the observations from the engagement of the strategic stakeholders (government officials) it was observed that there is the need for developing alternative guidelines that is suitable for the case study area. As a result, the study developed new guidelines and offered some policy recommendations (see sub-section 7.2) that will bring the desired change.

Also, another major important aspect of the study is that it has built new knowledge on the status quo and has established a synergy between science and society in the case study area. This synergy can be replicated across the various sedimentary basins (Sokoto, Bida, Benue and Gongola) of Nigeria. Furthermore, the socio-hydrogeological approach outlined in this study can bridge the gap between the local stakeholders (water users) and groundwater scientists (hydrogeologists). This can stimulate the perception of the citizenry towards the importance of hydrogeology to the society.

The major groundwater contamination problems are mainly attributed to the impact of pit latrines, open dump sites, and other non-point sources across the case study area. This study has identified and ranked the potential sources of groundwater contamination in the case study area in mitigating their impact on the underlying aquifer.

Geologically, the study has provided base line data on the petrographic, Granulometric, and mineralogical characteristics of the Quaternary sediments of the Nigerian sector (SW) of the Chad Basin. The study has identified and classified the primary, secondary, and accessory minerals that made up the Chad Formation, it has determined the grain sizes of the various aquifer materials as well as their chemical compositions.

The groundwater quality results suggest that the water quality is presently good for consumption and other domestic uses. The petrographic analyses suggests that the upper horizon of the sedimentary units of the case study area is dominated by fine grained materials which likely provided better physico-chemical barriers; due to their higher sorption capacity and relatively lower permeability than the coarse sands occurring at the base. In the case study area, it is likely that the above factors helped in minimising the amount of contaminants concentration in the groundwater.

This study modelled chloride concentration to provide better understanding on how they affect the quality of groundwater. The model is first of its kind in the study area and can be used as a decision support tool to solve existing and emerging groundwater management problems. The outputs of the model will be useful to the local stakeholders; especially the state policy makers and other relevant stakeholders in making informed management decisions.

Methodologically, the study has integrated the scientific (hydrogeological) and the social-strands in developing an alternative guidelines for the management of groundwater resources. This has strengthened the synergy between the two methodological dimensions. Therefore, by combining the two methodologies, groundwater scientists can manage the hydrogeological and social boundaries in ways that will simultaneously enhance the creditability and the legitimacy of their investigations. This can expand the new concept of people and water (socio-hydrogeology) in the case study area; this has great significance because this study has produced a base line data for achieving sustainable development in the region. Overall, the study has incorporated social dimensions into Hydrochemical investigations in addressing societal problems and in achieving sustainable management of vulnerable aquifers into the future.

In this study, the combination of the descriptive and inferential statistical methods and content analysis presented in the study are robust. This has informed the study about the relationships that exists between the various socio-environmental variables and it has enabled the researcher to test the accuracy of the different views of the stakeholders. Additionally, this view was also validated by the content analysis employed in the qualitative aspect of the study; where stakeholders expressed their views and opinions in the interviews and focus group discussions. The combination of multiple approaches to analysing quantitative and qualitative data enabled the development of the new guidelines presented herein.

Taking all the above mentioned statements into consideration, limitations exist in the study. The major limitations of the study as far as the Hydrochemical analyses is concerned is that the parameters selected and analysed are limited to anthropogenic activities related to the effects of urbanisation and population growth. These parameters are chloride, nitrate, phosphate and sulphates. Thus, it is noteworthy that complex hydrocarbons and their derivatives are not included. This aspect has not been addressed in the study because of the non-existent nature of the activities of the petroleum industry. However, the current agitation for harnessing the petroleum potentials in the Chad Basin (case study area) might likely affect the groundwater system in the future.

Moreover, some possible limitations that have not been discussed extensively are related to issues of groundwater management in the context of climate change. Although, aspects related to climate change conditions are greatly appreciated, their details in the context of this study are limited. It is paramount to stress that climate change in water governance needs to be considered in the context of sub-Saharan Africa in order to reduce vulnerability of the poor people of the region in maintaining decent and sustainable livelihoods.

Another limitation of this study is that it has not covered legal aspects related to the development and management of groundwater resources. Water legislation is usually difficult to craft, and therefore studies covering aspects of groundwater legislation should commence as soon as possible. Furthermore, the study is limited to the aspects related to the economics of groundwater management.

Major limitation exists in the modelling aspect of the study; the modelling exercise is theoretical at the moment; therefore, the comprehensiveness of the model can be questionable as the results of the model were not tested in real sense. Additionally, the guideline developed by the study has not been used by the primary stakeholders. However, the strategic (institutional) stakeholders have promised to integrate the guideline recommendations into their existing policies. It is noteworthy that these guidelines are not only limited to the Chad Basin alone, they can be transferred and applied in many sedimentary Basins of Africa. In this respect; it can be applicable in the Iullemmeden Basin, Benue Basin, Tindouf and Taudeni Basins in West Africa. Other Basins are Oulad Abdoun Basin, and the Sirte Basin in North Africa, and Congo Basin in East Africa. Also, the concepts of the study can be applicable in the sedimentary environments of the southern Africa region. On the basis of country by country the guidelines developed by the study can be applicable in almost all the sedimentary basins of the 53 countries of the African continent.

This is because most African countries are experiencing similar challenges attributed to uncontrolled urbanisation and population growth. Also, except for few countries, almost all the countries are confined to arid and semi-arid climates. Thus, the scope of the study in terms of implementation can go beyond the local case study area to cover all the areas of the semi-arid climate. The implementation of the guidelines developed herein requires incremental and radical approach to address the differences in opinion of the various stakeholder groups, in achieving sustainable development in the study area and the continent as a whole.

The recommendations proffered by this study can be implemented by the various local, state, national, and regional governments in collaboration with the relevant stakeholders across the study area and the continent. At, the local level, communities can be empowered by the local authorities to participate actively in groundwater management activities. Time scales of 1-30 years, can be set as short (1-10 years), medium (16-20 years), and long (21-30 years) terms respectively. These projections can be set to start the process of implementation. In this respect, detailed explanations on how to ensure the implementation of each policy is outlined below.

7.2 Policy Recommendations for Attaining a Viable groundwater System in Sub-Saharan Africa

Taking into account the analysis of the stakeholder engagement presented in chapter 5. It can be concluded that the solutions to the intractable issue of groundwater contamination as opined by the various stakeholder groups in the study requires an integrated approach and are urgently required. It can be assumed that the problems of groundwater management in Nigeria and many other countries in sub-Saharan Africa are similar in nature. In this regard, the following recommendations need to be considered in achieving sustainable management of water resources.

7.2.1 Educating the Citizenry on Groundwater Protection

Taking into consideration, evidences presented in the study on the lack of knowledge about groundwater contamination; especially in the focus group and household survey. There is the need to educate the citizenry on issues of groundwater protection. The first step of achieving this is by educating the general populous to create awareness among the general population on the benefits of safe, clean water and the environment. If not controlled, the water sources needed for future development and population growth are likely going to be degraded by current waste disposal practices and the stakeholders (especially those with low capacities) needs to be made aware of this to help curb contaminating practices. In this regard, the state government, through the ministry of education and the state primary education board, has an important role to play by reviewing the current curriculum to incorporate environmental education to the existing curriculum of education so that future actors (pupils) will recognise the importance of sustainability. At present, the National School Curriculum only recognised health education and social studies at pre and post-primary school levels.

7.2.2 Provision of Adequate Legislation for Participatory Water Management

The institutional stakeholders engaged via the interviews opined that current legislative framework is not very clear on the role of stakeholders in the management of groundwater resources. Also, the primary stakeholders engaged via the focus group and household surveys suggested that the adoption strict laws will address the

current problem. Thus, federal, state and local government authorities in Nigeria must liaise with the citizenry to introduce legislation that will define the role of stakeholders in groundwater development and legislations that will constrain the activities that might compromise groundwater quantity and quality.

7.2.3 Waste Management

Lack of concerns on issues of waste management was also pointed out by the interviewees, the focus group participants, and the household survey respondents. Thus, developing a robust waste management framework that considers the ethics, beliefs and cultural norms of the people is essential. For this reason, the state and local governments, and all other relevant institutions should adopt and implement programmes that will empower local women and youth groups through beneficial waste management activities. This has multiple benefits as it will ensure the protection of groundwater resources and the environment, this will help to prevent illnesses related to poor sanitary conditions. As an ancillary benefit it will create employment opportunities for the jobless women and youths who are typically the lowest income earners across the sub-region.

7.2.4 Institutional Integration and Streamlining of Responsibilities

The institutional stakeholders are of the opinion that there is no proper coordination among the local, national and international institutions on integrative management of water resources. Also, they pointed out that existing structure (top-down

governance) is a major impediment and often results in inconsistency of government policy implementation. Therefore, a more integrated governance framework that brings together the relevant stakeholders (government ministries, water user groups, academia/technical experts and all other relevant institutions) should be put in place, so that water and waste management are handled as a subsystem of a larger planning system, each impacting on the other. Additionally, the institutional framework for solid-waste management must be addressed, with a view of bringing together the relevant institutional players and clarifying their responsibilities in each case.

7.2.5 Additional Commitment by the Various Tiers of Government

All the institutional stakeholders are of the opinion that there is the need for further commitment by the various tiers of government in Nigeria. Thus, the federal, states, and local governments need to further commit their resources as contained in the national water policy in improving the access to safe, clean, and affordable water in the country. However, despite their commitments, the Millennium Development Goal (MDG) on access to water and sanitation remained unrealistic. Different countries have started the adoption and implementation of the Sustainable Development Goals (SDGs). There is the need for the various governments in the sub-region to fully localize the SDGs in prioritising the post-2015 development agenda for water resource management in their national and regional developmental policies. Also, it is equally important, for the sake of sustainable water resource management, to

ensure that there are adequate returns from cost recovery to finance data collection, monitoring of system status, and resources management.

7.3 Recommendations for Future Research

While the research activities reported in this thesis have addressed a number of critical issues relating to sustainable groundwater management in sub-Saharan Africa region, it is imperative to identify some key areas of research that would complement and progress the findings of the study. Consequently, the following recommendations are made for future research work;

- In the case study area and sub-Saharan Africa region, groundwater is strongly precipitation-dependent. This study has not directly investigated the impacts of climate variability on groundwater resources. Hence it is important to carry out further hydrological/hydrogeological research on the large-scale effects of climate change on the water resources (on a temporal and spatial scale) across the case study area and the entire sub-region.
- It is also imperative to evaluate the possibilities of groundwater contamination as a result of organic chemicals and heavy metals that have not been covered in this study. There is an urgent need to assess the extent of the problem and, ultimately, develop guidelines for the detection and evaluation of contamination caused by these chemicals.

- As groundwater is still viewed as a free good in the study area and many parts of Africa, there is the need for studies to focus on the aspects related to economics and accounting of groundwater resources. This will enable the derivation of the maximum benefits from the available groundwater resources. Therefore, studies that will focus on the opportunity costs involved in current and future allocation patterns are vital in this region.
- Socio-hydrogeology is still at its infancy, this study has attempted to take it to the next level. However, there is more to be done in this regard. Thus, social scientists, engineers, geologists and other relevant disciplines needs to take the social aspects of this study to the next level in understanding the sociology of groundwater management.
- Future studies should focus on extending the comprehensiveness of the model developed by this study. This should include testing the model including the determination of its effectiveness.
- Studies that focus on the monitoring and implementation of the guidelines developed by this study should be considered in the future. This will provide more details on the effectiveness of the guidelines in the future.

References

- Abdo, G., & Salih, A. (2012). Challenges Facing Groundwater Management in Sudan.
- Acharya, B. (2010). Methodology: social exclusion and group mobilization. *Contributions to Nepalese Studies* 36, Special Issue, pp. 23-47.
- Adelana, S. M. (2006). A quantitative estimation of groundwater recharge in parts of the Sokoto Basin, Nigeria. *Environ. Hydrol.* 14(5):105-119.
- Adelana, S. M., Olasehinde, P. I., Vrbka, P. (2003). Isotope and geochemical characterization of surface and subsurface waters in the semi-arid Sokoto Basin, Nigeria. *Afric. J. Sci. Tech., (AJST)*, 4(2): 80-89.
- Africa Infrastructure Country Diagnostic (AICD) (2011). Africa's Infrastructure: A Time for Transformation. African Development Bank Group, World Bank. Available: <http://www.infrastructure.org/aicd/library/doc/552/africa's-infrastructure-time> transformation [01/01/ 2013].
- Ahmed, M. F. (2002). A low cost technique of arsenic removal from drinking water by coagulation using ferric chloride salt and alum. *Water Science and Technology: Water Supply*, 2(2), 281-288.
- Akujieze, C. N., Coker, S. J., Oteze, G. E. (2003). Groundwater in Nigeria- a millennium experience-distribution, practise, problems and solutions. *Hydrogeology* 11(2):259-274.
- Al-Ahmari, M. (2006). Measuring Groundwater Contamination in Agricultural & Urban Areas Using GIS. [Online] available: http://faculty.kfupm.edu.sa/crp/bramadan/Term_051_CRP- [01/09/2014].
- Alexander, M. (2000), Aging, bioavailability and overestimation of risk from environmental pollutants. *Environ Sci Technol* 34:4259–4265
- Ali, A. F. (2012). Groundwater Pollution Threats of Solid Waste Disposal in Urban Kano, Nigeria: Evaluation and Protection Strategies. A PhD thesis submitted to The University of Manchester (unpublished).
- Aller, L., Bennett, T., Lehr, J. H., Petty, R. J., Hackett, G. (2003). DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings. *EPA-600/2-87-035*.
- Alley, W. M., and Leake, S. A. (2004). The journey from safe yield to sustainability. *Ground Water*, Vol. 42, No.1, January-February, 12-16.
- Almasri, M. N. (2007). Modeling nitrate contamination of groundwater in agricultural watersheds. *Journal of Hydrology*, 343(3), 211-229.
- Anderson, D.M., Kaoru, Y. & White, A. (2010). Estimated Annual Economic Impacts from Harmful Algal Blooms (HABs) in the United States. Woods Hole Oceanographic Institution Technical Report.
- Andrews, R. (2003). Research questions. Bloomsbury Publishing.

APHA (2013). Standards Methods for the Examination of water and wastewater (20th Ed.) Washington, DC: Am. Public Health Assoc.

Arnell, N. W. (1999). A simple water balance model for the simulation of stream flow over a large geographic domain. *Journal of Hydrology* 217, 314–335.

Atabey, E. (2005). In: Atabey, E. (ed) Publications of chamber of geology engineers of Turkey. TMMOB, Ankara.

Atmadja, J., and Bagtzoglou, A. C. (2001). Pollution Source Identification in Heterogeneous Porous Media. *Water Resour. Res.* 37, 2113-2125.

Ayenew, T., Masersha, P., and Seleshi, B. A. (2004) Ethiopia Country Report prepared for project: Groundwater in Sub-Saharan Africa: Implications for food security and livelihoods' International Water Management Institute, Sri Lanka.

Bagtzoglou, A. C. (1990). Particle-grid methods with application to reacting flows and reliable solute source identification. Ph.D. Dissertation, University of California Irvine, 246.

Bakari, A. (2014a). Hydrochemical assessment of groundwater quality in the Chad Basin around Maiduguri, Nigeria. *Journal of Geology and Mining Research*, 6(1), 1-12.

Bakari, A. (2014b). Assessing the Impact of anthropogenic activities on groundwater quality in Maiduguri, Nigeria.

Bakari, A. (2014c). An investigation of the physical and mineralogical characteristics of the quaternary formation of the Chad Basin, Nigeria. *International Journal of Scientific & Technology Research* 3 (8).

Barber, W., Jones, D. G. (1960). The Geology and Hydrogeology of Maiduguri, Borno Province. Records of the Geological Survey of Nigeria, pp. 5-20.

Barcelona, M. J. (1984). Chemical Problems in Ground-Water Monitoring Programs. In: Proceedings of the 3rd National Symposium on Aquifer Restoration and Ground-Water Monitoring, Columbus, OH, May 25-27, 1983, p. 263-271, D. M. Nielsen, cd., National Water Well Association, Water Well Journal Publishing Company, Worthington, Ohio, 461 pp.

Barcelona, M. J., Gibb, J. A. Helfrich E. E. (2004). Practical Guide for Ground-Water Sampling; U.S. Environmental Protection Agency, EPA/600/2-85/104, 169 pp.

Barcelona, M. J., Helfrich, J. A., and Garske, E. (2005). Sampling tubing effects on groundwater samples. *Anal. Chem.*, 57: 460.

Barry, B., and Obuobie, E. (2011) Status report on groundwater in Mali: Country Report prepared for project: 'Groundwater in Sub Saharan Africa: Implications for food security and livelihoods' International Water Management Institute, Sri Lanka.

Belton, V., & Stewart, T. (2002). *Multiple criteria decision analysis: an integrated approach*. Springer.

Benbasat, I., Goldstein, D. K., Mead, M., (1987). The case research strategy in studies of information systems. *MIS Quart.* 11 (3), 369–386.

Benjamini, Y., and Hochberg Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B (Methodological)* 57 (1), 289–300.

Benjamini, Yoav; Yekutieli, Daniel (2001). The control of the false discovery rate in multiple testing under dependency. *Annals of Statistics* 29 (4): 1165–1188

Bentley, R. A. (1986). The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. *Archaeometry*, 44(1), 117-135.

Berkes, F., Colding, J., and Folke, C., eds. (2003). *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*. Cambridge, UK: Cambridge Univ. Press

Berkowitz, B., Dror, I., & Yaron, B. (2008). Characterization of the Subsurface Environment. *Contaminant Geochemistry: Interactions and Transport in the Subsurface Environment*, 3-26.

Berkowitz, B., Dror, I., & Yaron, B. (2014). Selected Research Findings: Contaminant Transport. In *Contaminant Geochemistry* (pp. 285-345). Springer Berlin Heidelberg.

Bhaduri, B., Minner, M., Tatalovich, S. and Harbor, J. (2001). Long-term hydrologic impact of urbanization: A tale of two models. *Journal of Water Resources Planning and Management* 127(1), 13-19.

Biswas, A. K. (2004). *Appraising the Concept of Sustainable Development: Water Management and Related Environmental Challenges* (Oxford: Oxford University Press).

Blöschl G. (2011). Scaling in hydrology. *Hydrological Processes* 15: 709–711.

Bolan, N. S., Duraisamy, V. P., et al. (2003). Role of inorganic and organic soil amendments on immobilisation and phytoavailability of heavy metals: a review involving specific case studies. *Soil Research*, 41(3), 533-555.

Bollag, M. T., Liu, L. (1999). Fate of herbicides influenced by biotic and abiotic interactions. *Chemosphere*, 39(2), 333-341.

Borno State Government (BOSG) (2014). Information guide (online) pamphlet.

Borno State Government (BOSG). (2013). Borno state information and guide (online) available: <http://www.bornostate.gov.ng/> [12/04/2013].

Bouraoui, F., Vachaud, G. and Chen. T. (2008). Prediction of the effect of climatic changes and land use management on water resources. *Physics and chemistry of the earth* 23(4), 379-384.

Braune, E., Hollingworth, B., Xu, Y., Nel, M., Mahed, G., and Solomon, H. (2008). Protocol for the Assessment of the Status of Sustainable Utilization and Management of Groundwater Resources with Special Reference to Southern Africa, Water Research Commission. WRC report no TT 318/08.

Braune, K., Rual, J. F., Vazquez, A., Stelzl, U., Lemmens, I., Hirozane-Kishikawa, T., & Vidal, M. (2008). An empirical framework for binary interactome mapping. *Nature methods*, 6(1), 83-90.

Bregnard, T. P., Haner, A., Hohener, P., & Zeyer, J. (1997). Anaerobic degradation of pristane in nitrate-reducing microcosms and enrichment cultures. *Applied and Environmental Microbiology*, 63(5), 2077-2081.

British Geological Survey (BGS) (2002) Groundwater Fact Sheet: The Impact of Urbanisation.

British Geological Survey (BGS) (2003). Groundwater Quality: Nigeria

British Geological Survey, (2012). Groundwater in Africa. A strategic study. Groundwater issues. Report prepared by the British Geological Survey.

Broderick, J. et al. (2011). Shale gas: an updated assessment of environmental and climate change. A report commissioned by the co-operative. Tyndall centre, University of Manchester: Manchester

Broholm, M. M., & Arvin, E. (2000). Biodegradation of phenols in a sandstone aquifer under aerobic conditions and mixed nitrate and iron reducing conditions. *Journal of contaminant hydrology*, 44(3), 239-273.

Brown, R., Keath, N., & Wong, T. (2008). Transitioning to Water Sensitive Cities: Historical, Current and Future Transition States.

Buchanan, I. (1983). Ground Water Quality and Quantity Assessment. *J. Ground Water*. pp. 193-200.

Buede, D. (2013). Using multi criteria decision making in analysis of alternatives for selection of enabling technology. *Systems engineering*, 17(3), 288-304.

Bunu, Z. M. (1999). Groundwater Management Perspectives for Borno and Yobe States. *Journal of Environmental Hydrology* Vol. 7 Paper 19.

Burmaster, D. E. (1982). The new pollution: groundwater contamination. *Environment: Science and Policy for Sustainable Development*, 24(2), 6-36.

Burnard, P. (1991). A method of analysing interview transcripts in qualitative research. *Nurse Education Today* 11 (6), 461–466.

Burrell, G. and Morgan, G. (1979). *Sociological Paradigms and Organisational Analysis*. London: Heinemann.

Butler Jr, J. J. (2003). Hydrogeological methods for estimation of spatial variations in hydraulic conductivity. In *Hydrogeophysics* (pp. 23-58). Springer Netherlands.

Calabrese, E. J., Tuthill, R. W. (1985) The Massachusetts blood pressure study III. Experimental reduction of sodium in drinking water: effects on blood pressure. *Toxicol Ind Health* 1:19 – 34

Cannavo, P., Richaume, A., & Lafolie, F. (2004). Fate of nitrogen and carbon in the vadose zone: in situ and laboratory measurements of seasonal variations in aerobic respiratory and denitrifying activities. *Soil Biology and Biochemistry*, 36(3), 463-478.

Carrey, R., Otero, N., Vidal-Gavilan, G., Ayora, C., Soler, A., & Gómez-Alday, J. J. (2014). Induced nitrate attenuation by glucose in groundwater: Flow-through experiment. *Chemical Geology*, 370, 19-28.

Casey, F. X., Simunek, J., Lee, J., Larsen, G. L., & Hakk, H. (2005). Sorption, mobility, and transformation of estrogenic hormones in natural soil. *Journal of environmental quality*, 34(4), 1372-1379.

Casey, M. M. (2008). Using a socioecological approach to examine participation in sport and physical activity among rural adolescent girls. *Qualitative Health Research*, 19(7), 881-893.

Cervantes, C. (2001). Interactions of chromium with microorganisms and plants. *FEMS Microbiology Reviews*, 25(3), 335-347.

Chapman, D. (1996). Water quality assessments: a guide to the use of biota, sediments and water in environmental monitoring. Second edition. UNESCO/WHO/UNEP publication. (London: E & F N Spon.)

Chen, Z., Grasby, S. E., & Osadetz, K. G. (2004). Relation between climate variability and groundwater levels in the upper carbonate aquifer, southern Manitoba, Canada. *Journal of Hydrology*, 290(1), 43-62.

Chiang, W. H., Kinzelbach, S. (2001). 3D-groundwater modeling with PMWIN (Vol. 346, pp. 67744-5). Berlin, Heidelberg, New York: Springer-Verlag.

Chilton, P. J. (1998). Groundwater recharge and pollution transport beneath waste water irrigation: the case of León, Mexico. 153–168 in Groundwater pollution, aquifer recharge and vulnerability. Robins, N. S. (editor). Geological Society of London Special Publication, No. 130.

Chilton, P.J. (1992). Aquifers as environments for microbial activity. In: Proceedings of the International Symposium on Environmental Aspects of Pesticide Microbiology, Sigtuna, Sweden, 293-304.

Chilton, P.J. (1996). The impact of tropical agriculture on groundwater quality. In: H. Nash and G.J.H. McCall [Eds] Groundwater Quality, Chapman & Hall, London, 113-122.

Cho, J-C., Cho, H. B., and Kim, S-J. (2000). Heavy contamination of a subsurface aquifer and a stream by livestock wastewater in a stock farming area, Wonju, Korea. *Environmental Pollution*, 109, 137-146.

Cook, J M, Edmunds, W M, Kinniburgh, D K and Lloyd, B. (1989). Field techniques in groundwater quality investigations. British Geological Survey Technical Report WD/89/56.

Costanza, R. (2003). A vision of the future of science: reintegrating the study of humans and the rest of nature. *Futures*, (35), pp. 651-671.

Council of Canadian Academies (2009). The Sustainable Management of Groundwater in Canada. Available: <http://www.scienceadvice.ca/en/assessments/completed/groundwater.aspx> [23/01/2013].

Cox, L. A., (2008). What's wrong with Risk Matrices? *Risk Analysis*, Vol. 28, No.2. DOI:10.1111/j.1539-6924.2008.01030.x

Croke, B. F. W., & Jakeman, A. J. (2014). An open software environment for hydrological model assessment and development. *Environmental Modelling & Software*, 26(10), 1171-1185.

- Cronin, A., Pedley, S., Hoadley, A., Haldin, L., Gibson, J., & Breslin, N. (2004). Urbanisation effects on groundwater chemical quality: findings focusing on the nitrate problem from 2 African cities reliant on on-site sanitation. *Journal of water and health*, 5(3), 441-454.
- Datta, S. P. (2005). Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater—a case study. *Agriculture, Ecosystems & Environment*, 109(3), 310-322.
- De Carvalho, S. C. P., Carden, K. J., & Armitage, N. P. (2009). Application of a sustainability index for integrated urban water management in Southern African cities: case study comparison-Maputo and Hermanus. *Water SA*, 35(2), 144-151.
- De Vaus, D. (2001). Research design in social research. Sage.
- Dempster, H. S., Sherwood-Lollar, B., and Feenstra, S. (1997). Tracing organic contaminants in groundwater: a new methodology using compound specific isotopic analysis. *Environ. Sci. Technol.* 31, 3193-3197. No. 11.
- Denzin, N. K. (1978). The research act: A theoretical Introduction to Sociological Methods. New York: McGraw-Hill.
- Dexcel, (2004). Dexcel economic survey of New Zealand Dairy Farmers 2003-04. Hamilton, Dexcel.
- Diagana, B. (1994). Improving Water Supply Systems in Rural West and Central Africa, IDRC, workshop held in December 1994 in Cairo, Egypt.
- Dinar, A., and Saleth, R. M., (2005). Water institutional reforms: theory and practice. *Water Policy*, 7(1), 1-19.
- Diodato, N., and Ceccarelli, M. (2005). Interpolation processes using multivariate geostatistics for mapping of climatological precipitation mean in the Sannio Mountains (southern Italy), *Earth Surface Process, Landforms*, 30, pp.259–268.
- Domagalski, J. L, Johnson, H. (2012). Phosphorus and Groundwater: Establishing links between agricultural use and transport to streams: U.S. Geological Survey Fact Sheet 2012-300, 4 p.
- Dzwairo, B., Hoko, Z., Love, D. and Guzha, E. (2006). Assessment of the impacts of pit latrines on groundwater quality in rural areas: a case study from Marondera district, Zimbabwe. *Phys Chem Earth*, 31 (15-16), pp. 779-788.
- Dzwairo, B., Hoko, Z., Love, D., & Guzha, E. (2006). Assessment of the impacts of pit latrines on groundwater quality in rural areas: A case study from Marondera district, Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C*, 31(15), 779-788.
- Eckhardt, K., & Ulbrich, U. (2003). Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. *Journal of Hydrology*, 284(1), 244-252.
- Edmunds, W. M., Fellman, E., & Goni, I. B. (1999). Lakes, groundwater and palaeohydrology in the Sahel of NE Nigeria: evidence from hydrogeochemistry. *Journal of the Geological Society*, 156(2), 345-355.

Edmunds, W. M., Street-Perrott, G. (1996). Solute profile techniques for recharge estimation in semi-arid and arid terrain. In: Estimation of natural groundwater recharge. NATO ASI Series. Reidel, Dordrecht, pp 139–158.

Eugster, H. P., Maglione, G. (1979). Brines and evaporites of the Lake Chad basin, Africa. *Geochimica et Cosmochimica Acta* 43(7):973-981.

Evans, B., Gorelick, S. M & Remson, I. (2000). Identifying sources of groundwater pollution: An optimization approach. *Water Resources Research*, 19(3), 779-790.

Fan, A.M. and Steinberg, V.E. 1996. Health implications of nitrate and nitrite in drinking water: An update on methemoglobinemia occurrence and reproductive and developmental toxicity. *Regulatory Toxicology and Pharmacology*, 23, 35-43.

Ferrier, R. C., Wright, R. F., Cosby, B. J., and Jenkins, A. (1995). Application of the MAGIC model to the Norway spruce stand at Solling, Germany. *Ecol. Model.*, (83), pp. 77-84.

Fetter, K., Van Wilder, V., Moshelion, M., & Chaumont, F. (2004). Interactions between plasma membrane aquaporins modulate their water channel activity. *The Plant Cell Online*, 16(1), 215-228.

Fetter, S.(1994). The hazard posed by depleted uranium munitions. *Science & Global Security*, 8(2), 125-161.

Finegan, B. (1996). Pattern and process in neotropical secondary rain forests: the first 100 years of succession. *Trends in Ecology & Evolution*, 11(3), 119-124.

Flyvbjerg, B. (2011). Case study. In: Denzin N. K, Lincoln Y. S, editors. *The SAGE handbook of qualitative research*. 4th ed. Thousand Oaks, CA: Sage; 2011. pp. 301–316.

Fontana, A., & Frey, J. (2005). The art of science. *The handbook of qualitative research*, 361-376.

Fontana, V., Radtke, A., Bossi Fedrigotti, V., Tappeiner, U., Tasser, E., Zerbe, S., & Buchholz, T. (2013). Comparing land-use alternatives: Using the ecosystem services concept to define a multi-criteria decision analysis. *Ecological Economics*, 93, 128-136.

Fordyce, F. M. (2013). *Selenium deficiency and toxicity in the environment* (pp. 375-416). Springer Netherlands.

Foster, S. (2002). *Groundwater quality protection: a guide for water utilities, municipal authorities, and environment agencies*. Washington, DC: World Bank.

Foster, S. S. D., Chilton, P. J., Moench, M., Cardy, F., and Schiffler, M. (2000). Groundwater in rural development: facing the challenges of supply and resource sustainability. World Bank Technical Paper, No. 463 (Washington DC: World Bank), ISBN 0-8213-4703-9.

Foster, S. S. D., Lawrence, A. R., and Morris, B. L. (1998). Groundwater in urban development: assessing management needs and formulating policy strategies. World Bank Technical Paper, No. 390 (Washington DC: World Bank.)

Foster, S. S. D., Morris, B. L., and Lawrence, A. R. (1993). Effects of urbanisation on groundwater recharge. Procs of ICE International conference on groundwater problems in urban areas, London, June 1993. (London: Thomas Telford.)

Foster, S., & Garduño, H. (2013). Groundwater-resource governance: Are governments and stakeholders responding to the challenge? *Hydrogeology Journal*, 1-4.

Foster, S., Breach, M. & Mulenga, M. (2012). Urban groundwater use and dependency: Baseline Review of State of Knowledge and Possible Approaches to Inventory. Internal report to FAO Rome 33p

Foster, S., Garduno, H., Evans, R., Olson, D., Tian, Y., Zhang, W., & Han, Z. (2004). Quaternary aquifer of the North China Plain—assessing and achieving groundwater resource sustainability. *Hydrogeology Journal*, 12(1), 81-93.

Freeze, R. A., and Cherry, J. A. (1979). *Groundwater*, Prentice Hall, Inc, Upper Sadle River, New Jersey.

Friedman, A. L., & Miles, S. (2006). *Stakeholders: Theory and practice*. Oxford: Oxford University Press.

Galloway, D., David, R. J., and Ingebritsen, S. E. (1999). Land Subsidence in the United States, Washington, D.C., United States Geological Survey, Circular 1182, 177 pp.

Garduño, H., et al. (2013). Irrigated agriculture and groundwater resources—towards an integrated vision and sustainable relationship. *Integrated Water Resources Management in a Changing World: Lessons Learnt and Innovative Perspectives*, 35.

Garduño, H., van Steenberg, F., & Foster, S. (2010). Stakeholder participation in groundwater management. *GW Mate Briefing Note Series, Note,6*.

Garduño, P. Y. (2012). Social Safeguards for REDD+ in Mexico's Watershed Management Program.

Gaye, C. B., Edmunds, W. M. (1996). Groundwater recharge estimation using chloride, stable isotopes and tritium profiles in the sands of northwestern Senegal. *Environmental Geology*, 27 (3). 246-251.

Gibb, J. P., R. M. Schuller, and R. A. Griffin. (1981). Procedures for the Collection of Representative Water Quality Data from Monitoring Wells. Cooperative Groundwater Report 7, Illinois State Water Survey and Illinois State Geological Survey, Champaign, Illinois.

Gibs, J. and Imbrigiotta, T. E. (2002). Well-Purging Criteria for Sampling Purgeable Organic Compounds; *Ground Water*, Vol. 28, No. 1, pp 68-78.

Gillis, A and Jackson, W. (2002). *Research for nurses: Methods and interpretation*. Philadelphia: F.A Davis Company

Giordano, M., and Villholth, K. G. (eds.) (2007). *The Agricultural Groundwater Revolution: Opportunities and Threats to Development*. Wallingford: CABI.

Giupponi, C. (Ed.). (2006). *Sustainable management of water resources: an integrated approach*. Edward Elgar Publishing.

Glaser, F. (1997). Grounded theory: An exploration of process and procedure. *Qualitative health research*, 16(4), 547-559.

Gleeson, T., Wada, Y., Bierkens, M. F., & van Beek, L. P. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, 488(7410), 197-200.

Global Water Partnership (GWP). (2012). Integrated water resources management. TAC Background Paper No. 4. GWP, Stockholm, Sweden.

Gober, P., & Wheeler, H. S. (2014). Socio-hydrology and the science–policy interface: a case study of the Saskatchewan River basin. *Hydrology and Earth System Sciences*, 18(4), 1413-1422.

Goldstein, B. D., Kriesky, J., and Pavliakova, B. (2012). Missing from the table: role of the environmental public health community in governmental advisory commissions related to Marcellus shale drilling. *Environ Health Perspect*, 120 (4): p. 483-6.

Goni, I. B. (2006). The challenges of meeting domestic water supply in Nigeria. *J. Min. Geol.* 42(1):51-55.

Goni, I. B., Fellman, E., Edmunds, W. M. (2001). Rainfall geochemistry in the Sahel region of northern Nigeria. *Atmospheric Environment*, 35(25), 4331-4339.

Google earth (2014) Map of Maiduguri Nigeria [online] available: <https://www.google.com/maps/@37.0625,-95.677068,4z> [02/03/2014].

Graham, J. P., & Polizzotto, M. L. (2013). Pit latrines and their impacts on groundwater quality: a systematic review. *Environmental health perspectives*, 121(5), 521-530.

Greacen, J and Slivia, K. (2012). A comparison of low flow vs high flow sampling methodologies on groundwater metals concentrations. The Eighth National Outdoor Action Conference and Exposition, Minneapolis Convention Center, Minneapolis, Minnesota.

Grey, D. R. C., Kinniburgh, D. G., Barker, J. A. & Bloomfield, J. P. (1995). Groundwater in the U.K.A Strategic Study. Issues and Research Needs. Report FR/GF 1 (Marlow, UK: Groundwater Forum).

Guan, T. Y., and Holley, R. A. (2003). Pathogen survival in swine manure environments and transmission of human enteric illness: a review, *J Environ Qual*, 32(3):1153.

Guérin, V., Roy, S., & Ghestem, J. P. (2014). Quality assurance/quality control in groundwater sampling. *Quality assurance*, 128-144.

Gunderson, L. (1999). Resilience, flexibility and adaptive management: antidotes for spurious certitude? *Conserv. Ecol.* 3

Haliru, S. L, and Umar, D. A., (2012). Climate Change and Rural Water Supply Planning in Nigeria (eds) Walter, F. Climate Change and the Sustainable Use of Water resources, Springer-Verlag Berlin.

Hall, E. (2004). A double concern: grand mothers' experiences when a small grand child is critically ill. *Journal of Pedantic Nursing*. 19, pp. 61-69.

Hall, G E M, Bonham-Carter, G F, Horowitz, A J, Lum, K, Lemieux, C, Quemerais, B and Garbarino, J.R. (2006). The effect of using different 0.45µm filter membranes on 'dissolved' element concentrations in natural waters. *Applied Geochemistry*, Vol 11, 243-249.

Hallberg, G. R., & Keeney, D. R. (2003). Nitrate. In W. M. Alley (Ed.), *Regional ground-water quality*. US Geological Survey.

Hanley, N., Spash, C., & Walker, L. (1993). Problems in valuing the benefits of biodiversity protection. *Environmental and Resource Economics*, 5(3), 249-272.

Hanratty, M. P. and Stefan, H. G. (1998). Simulating climate change effects in a Minnesota agricultural watershed. *Journal of Environmental Quality* 27, 1524-1532.

Hare, M., Pahl-Wostl, C. (2002). Stakeholder categorization in participatory integrated assessment processes. *Integrated Assessment* 3, 50–62

Haria, H. A., Hodnett, M. G., Johnson, A. C. (2003). Mechanisms of groundwater recharge and pesticide penetration to a chalk aquifer in southern England. *J Hydrol* 275:122–137.

Hartley, J. (2004). *Case study research*, Sage Publishing, London.

Hartog, N., Van Bergen, P. F., De Leeuw, J. W., & Griffioen, J. (2004). Reactivity of organic matter in aquifer sediments: geological and geochemical controls. *Geochimica et Cosmochimica Acta*, 68(6), 1281-1292.

Hassett, J. J., & Banwart, W. L. (2009). The sorption of nonpolar organics by soils and sediments. *Reactions and movement of organic chemicals in soils, (reactionsandmov)*, 31-44.

Hayes, M. H. B., Clapp, C. E., & Mingelgrin, U. (2001). Measurements of sorption-desorption and isotherm analyses. *Humic substances and chemical contaminants, (humicsubstancesa)*, 205-240.

Hem, J.D. (1985). *Study and interpretation of the chemical characteristics of natural water* (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Henley, D. (2000). *Nigeria Water Supply and Sanitation Strategy*, Nigeria Water Sector. [Online] available: www.nws.org/henley/Nwss/strategy.pdf [03/04/2013].

Hirschheim, R. and Klein, H. (1994). Realising Emancipatory Principles in Information Systems Development: The Case of Ethics, *MIS Quarterly*, 18(1), 83-109.

Holling, C. S. (1978). *Adaptive Environmental Assessment and Management*. London: Wiley

Houghton, J. T., et al. (2001). *Climate Change 2001: The Scientific Basis*. Cambridge university press.

Howard, K. James, W., and White, F. (2003). Incorporating policies for groundwater protection into the urban planning process. In Chilton, J. et al. (Eds), *Groundwater in the urban environment: problems, processes and management* (pp. 31-40). Rotterdam: Balkema Publishers.

Huntjens, P., Kool, J., Lasage, R., Sprengers, C., Ottow, B., & Kerssens, P. (2013). Preferred Climate Change Adaptation Strategy for the Lower Vam Co River Basin, Long An Province.

International Association of Hydrogeologists (IAH). (2006). *Groundwater in Fractured Rocks: IAH Selected Paper Series, Volume 9*.

IPCC (International Panel on Climate Change) (2007). Climate Change and Water. Technical Paper of the intergovernmental Panel on Climate Change. Geneva, Switzerland, IPCC Secretariat.

IPCC. (2007). Climate change 2007: The IPCC fourth assessment report. Cambridge: IPCC reports, Cambridge University Press.

Jacks, G., F. Sefe, M. Carling, M. Hammar, and P. Letsamao. "Tentative nitrogen budget for pit latrines—eastern Botswana." *Environmental Geology* 38, no. 3 (1999): 199-203.

Jaekel, D. (1984). Rainfall patterns and lake level variations at Lake Chad: in climatic changes on a yearly to millennial basis, Geological, Historical and Instrumental Records, Morner N, and Karlen W, Eds D. Reidel Publ. co. Dordrecht, Netherlands, pp. 191-200.

Jakeman, A. J., Letcher, R. A. (2003). Integrated assessment and modelling: features, principles and examples for catchment management. *Environmental Modelling and Software*, (18), pp. 491-501.

Johnson, N., Lilja, N., Ashby, J.A., Garcia, J.A., (2004). Practice of participatory research and gender analysis in natural resource management. *Natural Resources Forum* 28, 189–200.

Journel, A. G., Huijbregts, C.J. (1978). *Mining Geostatistics*. Academic Press, London (1978), p. 600.

Kashaigili, J. J. (2003). Current Utilization and Benefits Gained from Wetlands in the Usangu Plains (Draft report HRPWET3) 49p.

Kearl, P M, Korte, N E, Stites, M and Baker, J. (2012). Field comparison micropurging vs. traditional ground water sampling. *Groundwater Monitoring & Remediation*, Vol.14, No. 4, 183-190.

Keeney, D. R., DeLuca, T. H., & McCarty, G. W. (2002). Effect of freeze-thaw events on mineralization of soil nitrogen. *Biology and Fertility of Soils*, 14(2), 116-120.

Kelle, L. (2006). *Strategic brand management: Building, measuring, and managing brand equity*. Pearson Education India.

Kelly, W., Ray, A. (1999). Impact of irrigation on the dynamics of nitrate movement in a shallow sand aquifer, Illinois state water survey Chittaranjan Ray, University of Hawaii at Manoa, Research report 128.

Kemper, E., Stringfield. S., & Teddlie, C. (2004). Mixed methods sampling strategies in social science research. In A. Tashakkori & C. Teddlie (Eds.), *Handbook of mixed methods in social & behavioural research* (pp. 273-296). Thousand Oaks, CA: Sage.

Kemper, K., & Alvarado, O. (2001). *Water in Mexico A Comprehensive Development Agenda for the New Era*. Washington, DC, USA: World Bank, 619-643.

Khazai, E., and Riggi, M. G. (1999). Impact of urbanization on the Khash aquifer, an arid region of south east Iran. In Ellis J. B. (Ed.), *Impacts of urban growth on surface water and groundwater quality: proceedings of an international symposium held during IUGG 99, the XXII General Assembly of the International Union of Geodesy and Geophysics*, at

Birmingham, UK 18-30 July 1999. Wallingford: IAHS.

Kinzelbach, W., Schaffer, W., Herzer, J. (2003): Numerical modelling of natural and enhanced denitrification in aquifers. *Water Resour. Res.* 27(6), 1123-1135.

Kiptum, C. K., & Ndambuki, J. M. (2012). Well water contamination by pit latrines: a case study of Langas. *International Journal of Water Resources and Environmental Engineering*, 4(2), 35-43.

Klein, H. and Myers, M. (1999). A Set of Principles for Conducting and Evaluating Interpretive Field Studies in Information Systems. *MIS Quarterly*, 23(1), 67-94.

Knüppe, K. (2011). The challenges facing sustainable and adaptive groundwater management in South Africa. *Water SA*, 37(1), 67-79.

Knüppe, K., & Pahl-Wostl, C. (2012). Requirements for adaptive governance of groundwater ecosystem services: insights from Sandveld (South Africa), Upper Guadiana (Spain) and Spree (Germany). *Regional Environmental Change*, 13(1), 53-66.

Konikow, L. F., Sanford, W. E., & Campbell, P. J. (1996). Constant-concentration boundary condition: Lessons from the HYDROCOIN variable-density groundwater benchmark problem. *Water Resources Research*, 33(10), 2253-2261.

Kretsinger, V. G., Narasimhan, T. N. (2005). Sustaining groundwater resources: California's shift toward more effective groundwater management. *Southwest Hydrol.*, 4: 18-19.

Krueger, R.A., & Casey, M.A. (2000). Focus groups: A practical guide for applied research (4th Ed.). Thousand Oaks, CA: Sage Publications.

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Jimenez, B., Miller, K., and Shiklomanov, I. (2008). The implications of projected climate change for freshwater resources and their management.

Lacroix, E., Brovelli, A., Holliger, C., & Barry, D. A. (2014). Control of groundwater pH during bioremediation: Improvement and validation of a geochemical model to assess the buffering potential of ground silicate minerals. *Journal of contaminant hydrology*, 160, 21-29.

Lake, W. B. and Souré, M. (1997). Water and Development in Africa. International Development Information Centre. Available: <http://www.acdi> [03/05/2012].

Lakshmanan, E., Kannan, R., Kumar, M. S. (2003). Major ion chemistry and identification of hydrogeochemical processes of ground water in a part of Kancheepuram district, Tamil Nadu, India. *Environmental geosciences*, 10(4), 157-166.

Langman, P., Nicholson, A. G., Rice, A., & Addis, B. (2008). Interobserver variation in the classification of thymic tumours—a multicentre study using the WHO classification system. *Histopathology*, 53(2), 218-223.

Langmuir, D. (1997). Aqueous environmental chemistry. Upper Saddle River, NJ: Prentice-Hall.

Lapworth, D. J., Baran, N., Stuart, M. E., & Ward, R. S. (2012). Emerging organic contaminants in groundwater: a review of sources, fate and occurrence. *Environmental Pollution*, 163, 287-303.

Lavoie, R., Joerin, F., & Rodriguez, M. J. (2014). Incorporating groundwater issues into regional planning in the Province of Quebec. *Journal of Environmental Planning and Management*, 57(4), 516-537.

Leavesley, G. H. (1994). Modeling the effects of climate change on water resources--A review, *Clim. Change*, 28, 159-177.

Levallois, P., Thériault, M., Rouffignat, J., Tessier, S., Landry, R., Ayotte, P., et al. (1998). Groundwater contamination by nitrates associated with intensive potato culture in Québec. *The Science of the Total Environment*, 217, 91–101. Doi:10.1016/S0048-9697(98) 00191-0.

Lewis, W. J., Farr, J. L., & Foster, S. S. (1980). THE POLLUTION HAZARD TO VILLAGE WATER SUPPLIES IN EASTERN BOTSWANA. *Proceedings of the Institution of Civil Engineers*, 69(2), 281-293.

Ligmann-Zielinska, A., & Jankowski, P. (2014). Spatially-explicit integrated uncertainty and sensitivity analysis of criteria weights in multicriteria land suitability evaluation. *Environmental Modelling & Software*, 57, 235-247.

Ligmann-Zielinska, A., & Jankowski, P. (2014). Spatially-explicit integrated uncertainty and sensitivity analysis of criteria weights in multicriteria land suitability evaluation. *Environmental Modelling & Software*, 57, 235-247.

Lindenberg, M.M., Crosby, B.L. (1981). *Managing Development: the Political Dimension*. Kumarian Press, West Hartford, CT

Llamas, M. R., Martinez-Santos, P., & de la Hera, A. (2006). The manifold dimensions of groundwater sustainability: An overview. In *The global importance of groundwater in the 21st Century: Proceedings of the international symposium on groundwater sustainability* (pp. 24-27).

Llamas, M. R., Martinez-Santos, P., & de la Hera, A. (2006). The manifold dimensions of groundwater sustainability: An overview. In *The global importance of groundwater in the 21st Century: Proceedings of the international symposium on groundwater sustainability* (pp. 24-27).

Loucks, D. P. (2000) Sustainable water resources management. *Water Int.* 25 (1) 3-10.

Loucks, D. P., and Gladwell, J. S. (1999). *Sustainability criteria for water resource systems*, Cambridge, UK.

Lovely, D.R., (1993). Dissimilatory metal reduction. *Ann. Rev. Microbiol* 47, 263-290.

Mabin, S., & Beattie, J. (2006). Ranking and rating multi-criteria decision-making method for facility site selection. *The International Journal of Production Research*, 59(12), 2313-2330.

MacDonald, A. M., & Davies, J. (2000). A brief review of groundwater for rural water supply in sub-Saharan Africa.

MacDonald, A. M., Lapworth, D. J., Hughes, A. G., Auton, C. A., Maurice, L., Finlayson, A., & Goody, D. C. (2014). Groundwater, flooding and hydrological functioning in the Findhorn floodplain, Scotland.

Maconachie, R. (2009). Diamonds, governance and 'local' development in post-conflict Sierra Leone: Lessons for artisanal and small-scale mining in sub-Saharan Africa? *Resources Policy*, 34(1), 71-79.

MacQuarrie, K. T., Sudicky, E. A., & Robertson, W. D. (2001). Numerical simulation of a fine-grained denitrification layer for removing septic system nitrate from shallow groundwater. *Journal of contaminant hydrology*, 52(1), 29-55.

MacRae, J. D., & Hall, K. J. (1998). Biodegradation of polycyclic aromatic hydrocarbons (PAH) in marine sediment under denitrifying conditions. *Water science and technology*, 38(11), 177-185.

Madriz, E. (2003). Focus groups in feminist research. In N. K. Denzin & Y. S. Lincoln (Eds.), *Collecting and interpreting qualitative materials*, 2nd edition (pp. 363-388). Thousand Oaks, CA: Sage Publications.

Maduabuchi, C., Faye, S., Maloszewski, P. (2006). "Isotope evidence of palaeorecharge and palaeoclimate in the deep confined aquifers of the Chad Basin, NE Nigeria. *Environment* 370(1):467-479.

Mahar, P. S., & Datta, B. (2001). Identification of pollution sources in transient groundwater systems. *Water Resources Management*, 14(3), 209-227.

Mahvi, A. H., Nouri, J., Babaei, A. A., Nabizadeh, R. (2005). Agricultural activities impact on groundwater nitrate pollution. *Int. J. Environ. Sci. Tech.*, 2 (1), 41-47

Mansuy, L., Philp, R. P., and Allen, J. (1997). Source identification of oil spills based on the isotopic composition of individual components in weathered oil samples. *Environ. Sci. Technol.* 31, 3417-3425. No. 12.

Maps online. (2014). Administrative and Political Map of Nigeria [online]. Available: http://www.nationsonline.org/oneworld/map/nigeria_map2.htm [22/04/2014].

Masiyandima, M. (2002) Sub-Saharan Africa: opportunistic exploitation. In: Giordano M and Villholth K (eds.) *the Agricultural Groundwater Revolution: Opportunities and Threats to Development*. Comprehensive Assessment of Water Management in Agriculture Series 3. IWMI and CAB International, Wallingford.

Mason, R. (1996). Computer-mediated communication. *Handbook of research for educational communications and technology*, 2, 397-431.

Matsunaga, L. J., & Liss, P. S. (1993). Photochemically induced redox reactions in seawater, I. Cations. *Marine chemistry*, 49(2), 201-213.

McBride, M. B. (1994). *Environmental chemistry of soils*. Oxford University Press

McDonald, M. G., & Harbaugh, A. W. (1988). A modular three-dimensional finite-difference ground-water flow model.

McDowell-Boyer L, Hunt JR, Sitar, N. (1986), Particle transport through porous media. *Water*

- Mcgrath, D., & Zhang, C. (2003). Spatial distribution of soil organic carbon concentrations in grassland of Ireland. *Applied Geochemistry*, 18, 1629–1639. doi:10.1016/S0883-2927(03)00045-3.
- McMahon, M. (1995). Conversations on clinical supervision: Benefits perceived by school counsellors. *British Journal of Guidance and Counselling*, 28(3), 339-351.
- McNamara, C. (1999) General Guidelines for Conducting Interviews. [Online] available: <http://www.mapnp.org/library/evaluatn/interview.htm> [03/05/2014].
- Meissner, R., Seeger, J., Rupp, H. and Balla, H. (1999). Assessing the impacts of agricultural land use changes on water quality. *Water Science Technology* 40(2), 1-10.
- Mendes, M. P., & Ribeiro, L. (2014). The importance of groundwater for the delimitation of Portuguese National Ecological Reserve. *Environmental Earth Sciences*, 1-11.
- Miller, J. and Glassner, B. (1997) The “Inside” and the “Outside”: Finding Realities in Interviews’, in D. Silverman (ed.) *Qualitative Research: Theory, Method and Practice*. London, Thousand Oaks, CA & New Delhi: Sage Publications.
- Miller, R. E., Johnston, R. H., Olowu, J. A. I., Uzoma, J. U. (1968). Groundwater hydrology of the Chad Basin in Borno and Dikwa Emirates, with special emphasis on the flow life of the artesian system. USGS Water Supply Paper. 1757.
- Milly, P. C., Betancourt, J., Falkenmark, M. (2008). Climate Change: Stationarity Is Dead: Whither Water Management? *Science* 319 (5863): 573 – 574.
- Ministry of Water of Zimbabwe (1987). Zimbabwe National Water Master Plan. Hydrogeology Vol. 1987. Harare.
- Mitchell, R. K., Agle, B. R., and Wood, D. J. (1997). Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts. *Academy of Management Review* 22(4): 853–886.
- Molle, F. (2009). River-basin planning and management: the social life of a concept. *Geoforum*, 40(3), 484-494.
- Mondal, N. C., Singh, V. P., Singh, V. S., & Saxena, V. K. (2010). Determining the interaction between groundwater and saline water through groundwater major ions chemistry. *Journal of Hydrology*, 388(1), 100-111.
- Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L. & Belyaev, V. (2013). “Panta Rhei—Everything Flows”: Change in hydrology and society—The IAHS Scientific Decade 2013–2022. *Hydrological Sciences Journal*, 58(6), 1256-1275.
- Morgan, D.L. (Ed.) (1997). *Successful focus groups: Advancing the state of the art*.
- Morgan, J. A., King, J. Y., LeCain, D., & Milchunas, D. G. (2002). Soil-atmosphere exchange of CH₄, CO₂, NO_x, and N₂O in the Colorado shortgrass steppe under elevated CO₂. *Plant and Soil*, 240(2), 201-211.
- Morris, B. L., Lawrence, A. R., Chilton, P.J., Adams, B., Calow, R.C., and Klinck, B.A. (2003). Groundwater and its susceptibility to degradation: A global assesment of the problem

and options for management. Early Warning and Assessment Report Series, RS.03-3. United Nations Environment Programme, Nairobi, Kenya.

Mumma, A., Lane, M., Kairu, E., Tuinhof, A., & Hirji, R. (2011). Kenya Groundwater Governance Case Study.

Narasimhan, T.N. and V. Kretsinger. 2003. Developing, managing and sustaining California's groundwater resources. A White Paper for the Groundwater Resources Association of California available: http://www.grac.org/CA_GW_Resources.pdf [01/11/2013].

National Groundwater Association, (2010) Facts about Global Groundwater Usage. Available: <http://www.ngwa.org/Fundamentals/use/Documents/global-groundwater-use-fact-sheet.pdf> [22/01/2014].

National Population Commission Nigeria. (2009). Nigeria Demographic and Health Survey 2009, Abuja, Nigeria/Calverton, MD: National Population Commission/ICF Macro.

National Research Council, (2003). Groundwater vulnerability assessment, contamination potential under conditions of uncertainty. Committee on Techniques for Assessing Ground Water Vulnerability, Water Science and Technology Board, Washington, D. C.

Ndirirtu, P. G., and Gitahae, I. T. (2011) Kenya. Country Report prepared for project: 'Groundwater in Sub-Saharan Africa: Implications for food security and livelihoods' International Water Management Institute, Sri Lanka.

Newson, M. (2009). *Land, water and development: sustainable and adaptive management of rivers*. Routledge.

Nichols, D. S., Prettyman, D., & Gross, M. (2003). Movement of bacteria and nutrients from pit latrines in the boundary waters canoe area wilderness. *Water, Air, and Soil Pollution*, 20(2), 171-180.

Nonde, A. (2011) Zambia. Country Report prepared for project: 'Groundwater in Sub-Saharan Africa: Implications for food security and livelihoods' International Water Management Institute, Sri Lanka.

Nwankwoala, H. O. (2011). The role of communities in improved rural water supply systems in Nigeria: management module and its implications for vision 20: 2020. *Journal of Applied technology in Environmental Sanitation*, 1(3), 295-302.

Oades, J. M., and Muneer, M. 1989). The role of Ca-organic interactions in soil aggregate stability. I. Laboratory studies with glucose ^{14}C , CaCO_3 and CaSO_4 . 2. H_2O . *Soil Research*, 27(2), 389-399.

Oats, R. (2006). Organizational ambidexterity in action: how managers explore and exploit, *California Management Review*, 53(4), 5-22.

Obaje, N. (2009). *Geology and Mineral Resources of Nigeria*. Springer-verlag, Berlin Heidelberg. ISBN 978-3-540-92684-9.

Obuobie, E and Barry, B. (2004). Groundwater Socio-Ecology of Ghana. IWMI-OPEC funded groundwater project studies in selected Sub-Sahara African countries. Ghana country report. IWMI Ghana. 41pp.

Odada, E. O., Oyebande, L., Oguntola, J. A. (2006). Lake Chad. Experience and Lessons Learned Brief. Lake Basin Management Initiative (LBMI) Experience and Lessons Learned Briefs.

Offodile, M. E. (1992). An approach to groundwater study and development in Nigeria. Mecon Services Ltd. pp. 66-78.

Olshansky, Y., Polubesova, T., Vetter, W., & Chefetz, B. (2011). Sorption–desorption behavior of polybrominated diphenyl ethers in soils. *Environmental Pollution*, 159(10), 2375-2379.

Onemano, J. I., and Otun, J. A. (2003). *Problems on water quality standards and monitoring in Nigeria: Towards the millennium development goals*. 29th WEDC International Conference, Abuja, Nigeria.

Oteze, G. E., Fayose, S. A. (1988). Regional development in the Hydrology of Chad basin. *Water Resour.* 1(1):9-29.

Pabich, W. J., Valiela, I., & Hemond, H. F. (2001). Relationship between DOC concentration and vadose zone thickness and depth below water table in groundwater of Cape Cod, USA. *Biogeochemistry*, 55(3), 247-268.

Pahl-Wostl, C. (2007). Transitions towards adaptive management of water facing climate and global change. *Water Resources Management* 21: 49-62.

Pahl-Wostl, Tabara, C. D., Bouwen, R., Craps, M., Dewulf, A., Mostert, E., Ridder, D., and Tailieu, T. (2008). The importance of social learning and culture for sustainable water management. *Ecological Economics* 64: 484-495.

Pallant, J. F. (2005). An introduction to the Rasch measurement model: an example using the Hospital Anxiety and Depression Scale (HADS). *British Journal of Clinical Psychology*, 46(1), 1-18.

Parker, L V and Clark, C H. (2002). Study of five discrete interval type groundwater sampling devices. US Army Corps of Engineers Technical Report, ERDC/CRREL TR-02-12.

Parker, P., Letcher, R., Jakeman, A., Beck, M. B., Harris, G., Argent, R. M., ... & Bin, S. (2002). Progress in integrated assessment and modelling. *Environmental Modelling & Software*, 17(3), 209-217.

Patten, M.Q. (2001). *Qualitative evaluation and research methods* (2nd ed.). Newbury Park, CA: Sage.

Paul, D. R., & Clark, R. (2002). Modeling of modified atmosphere packaging based on designs with a membrane and perforations. *Journal of Membrane Science*, 208(1), 269-283.

Pavelic, P., Smakhtin, V., Favreau, G., and Villholth, K. G. (2012) Water-balance approach for assessing potential for small holder groundwater irrigation in Sub-Saharan Africa. *Water SA* Vol. 38 No. 3.

Pavelic, Paul; Villholth, Karen G.; Verma, Shilp. (Eds.) (2013). *Sustainable groundwater development for improved livelihoods in Sub-Saharan Africa. Part 2*. Water International, 38(6):790-863. (Special issue with contributions by IWMI authors).

Peach, D. W., Adams, B., Bloomfield, J. P. & Wheeler, H. S. (2000) Support for integrated groundwater/surface water monitoring and sustainable catchment management, in: Sillio, O. et al. (Eds) *Groundwater: Past Achievements and Future Challenges*, pp 1017–1021 (Balkema).

Petersen, C. J., Graybosch, R. A., Baenziger, P. S., & Shelton, D. R. (1995). Environmental modification of hard red winter wheat flour protein composition. *Journal of Cereal Science*, 22(1), 45-51.

Phillips, R. (2003). *Stakeholder Theory and Organizational Ethics*, Berrett-Koehler Publishers Inc.

Pierzynski, G. M., Vance, G. F., & Sims, J. T. (2005). *Soils and environmental quality*. CRC press.

Preskill, H. (2006). Background and Foundational Information. *Health Informatics: An Interprofessional Approach*, 7(3), 83.

Price, M., Low, R. G., & McCann, C. (2000). Mechanisms of water storage and flow in the unsaturated zone of the Chalk aquifer. *Journal of Hydrology*, 233(1), 54-71.

Pujari, S., Keaton, M. A., Chaikin, P. M., & Register, R. A. (2012). Alignment of perpendicular lamellae in block copolymer thin films by shearing. *Soft Matter*, 8(19), 5358-5363.

Punch, S. (1998). Interviewing strategies with young people: the 'secret box', stimulus material and task-based activities. *Children & Society*, 16(1), 45-56.

Quevauviller, P. (2009). From the 1996 groundwater action programme to the 2006 groundwater directive—what have we done, what we learnt, what is the way ahead? *J Environ Monit* 10:408–421

Rabus, R., & Widdel, F. (1996). Anaerobic oxidation of the aromatic plant hydrocarbon p-cymene by newly isolated denitrifying bacteria. *Archives of microbiology*, 172(5), 303-312.

Rachdawong, P., and Christensen, E. (1997). Determination of PCB sources by a principal component method with nonnegative constraints. *Environ. Sci. Technol.* 31, 2686-2691. No. 9.

Radhakrishna, R. B. (2007). Tips for developing and testing questionnaires/instruments. *Journal of Extension*, 45(1), 1-4.

Re, V. (2015). Incorporating the social dimension into hydrogeochemical investigations for rural development: the Bir Al-Nas approach for socio-hydrogeology. *Hydrogeology Journal*, DOI 10.1007/s10040-015-1284-8.

Reed, M. S. (2009). Stakeholder participation for environmental management: a literature review. *Biological conservation*, 141(10), 2417-2431.

Reed, M. S., Stringer, L. C., Fazey, I., Evely, A. C., & Kruijsen, J. H. J. (2014). Five principles for the practice of knowledge exchange in environmental management. *Journal of environmental management*, 146, 337-345.

Reed, M.S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, H. C., and Stringer, L. C. (2008). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management* 90, 1933-1949.

Reineke, T. M. (2001). Modular chemistry: secondary building units as a basis for the design of highly porous and robust metal-organic carboxylate frameworks. *Accounts of Chemical Research*, 34(4), 319-330.

Remenyi, D., Williams, B., Money, A. and Swartz, E. (2002). *Doing Research in Business and Management: An Introduction to Process and Methods*. London: Sage.

Resour Res 22:1901–1921.

Rodvang, S., & Simpkins, W. (2001). Agricultural contaminants in Quaternary aquitards: A review of occurrence and fate in North America. *Hydrogeology Journal*, 9(1), 44-59.

Ross, C., and Donnison, J. (2003). Economics and adoption of conservation biological control. *Biological control*, 45(2), 272-280.

Rotmans, J. (2000). More evolution than revolution: transition management in public policy. *Foresight* 3, no. 1: 15–31.

Sabatier, P. A. (1999). The advocacy coalition framework, an assessment. In: Sabatier PA (ed) *Theories of the policy process*. Westview Press, Oxford.

Salman, M. A. (1999). Groundwater: Legal and Policy Perspectives. Proceedings of World Bank seminar. The World Bank, Washington D. C.

Sanni et al. (2012) Spatio-Temporal Variation of Drought Severity in the Sudano-Sahelian Region of Nigeria: Implications for Policies on Water Management. Springer-Verlag Berlin.

Saunders, M. R., Markie-Dadds, C., Rinaldis, M., Firman, D., & Baig, N. (2007). Using household survey data to inform policy decisions regarding the delivery of evidence-based parenting interventions. *Child: Care, Health and Development*, 33(6), 768-783.

Savenije, H. H. G., and Van der Zaag, P. (2008). Integrated water resources management: Concepts and issues. *Physics and Chemistry of the Earth* 33. 290–297.

Schlager, E. (2007). Community management of groundwater. In *The Agricultural Groundwater Revolution: Opportunities and Threats to Development*, ed. Mark Giordano and Karen G. Villholth: 131-152. Cambridge, MA: CABI.

Schmoll, O. et al., (Ed.). (2006). *Protecting groundwater for health: managing the quality of drinking-water sources*. World Health Organization.

Schot, J., and Geels, F. W. (2008). Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. *Technology Analysis & Strategic Management* Vol. 20, No. 5, 537–554.

Schwartz, F. W. and M. Ibaraki (2011). Groundwater: A Resource in Decline. *Elements* 7(3): 175-179.

Seiler, M., Vomberg, J. (2005). Nitrate occurrence and attenuation in the major aquifers of England and Wales. *Quarterly Journal of Engineering Geology and Hydrogeology*, 40(4), 335-352.

Seth, O. N., Tagbor, T. A., & Bernard, O. (2014). Assessment of chemical quality of groundwater over some rock types in Ashanti Region, Ghana.

Shah, T., Molden, D., Sakthivadivel, R., & Seckler, D. (2000). Groundwater: Overview of Opportunities and Challenges. IWMI.

Shiklomanov, I.A. (1999). World Water Resources and their Use, Paris, UNESCO.

Shiva, V. (2002). From water crisis to water culture. *Cultural Studies*, 22(3-4), 498-509.

Shove, E., & Walker, G. (2007). CAUTION! Transitions ahead: politics, practice, and sustainable transition management. *Environment and Planning A*, 39(4), 763-770.

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. T. (2010). Groundwater use for irrigation—a global inventory. *Hydrology and Earth System Sciences Discussions*, 7(3), 3977-4021.

Simes RJ (1986) An improved Bonferroni procedure for multiple tests of significance. *Biometrika* 73:751–754.

Simon, G. M. (2009). Activity-based proteomics of enzyme superfamilies: serine hydrolases as a case study. *Journal of Biological Chemistry*, 285(15), 11051-11055.

Singleton, M. J, Woods, K. N., Conrad, M. E., Depaolo, D. J., Dresel, P. E (2005). Tracking sources of unsaturated zone and groundwater nitrate contamination using nitrogen and oxygen stable isotopes at the Hanford site, Washington. *Environ. Sci. Technol.* 39:3563-3570.

Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C. A. & Rodríguez-Iturbe, I. (2014). Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future*, 2(4), 225-230.

Sivapalan, M., Yaeger, M. A., Harman, C. J., Xu, X., & Troch, P. A. (2011). Functional model of water balance variability at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry. *Water Resources Research*, 47(2).

Smedana, L. K., and Shiati, K. (2002). Irrigation and salinity: a perspective review of the salinity hazards of irrigation development in the arid zone. *Irrigation and Drainage Systems* 16 (2) 161-174.

Smith, H., Blackstock, K., and Wall, G. (2011). River basin planning meets spatial planning. Knowledge Scotland.

Smith, S. C., Fredrickson, J. K., & Liu, C. (2001). Dissimilatory bacterial reduction of Al-substituted goethite in subsurface sediments. *Geochimica et Cosmochimica Acta*, 65(17), 2913-2924.

Snodgrass, M. F., and Kitanidis, P. K. (2007). A geostatistical approach to contaminant source identification. *Water Resour. Res.* 33, 537-546. No. 4.

Song, Y., & Müller, G. (1999). Sediment-Water interactions in anoxic Freshwater sediments. Lecture Notes in Earth Sciences, Berlin Springer Verlag, 81.

Sparks, D. L., (ed) (2006). Soil physical chemistry. CRC Press, Boca Raton, Florida

Squillace, P. J, Scott, J. C., Moran, M. J., Nolan, B. T., Kolpin, D. W. (2002). VOCs, pesticides, nitrate, and their mixtures in groundwater used for drinking water in the United States. Environ. Sci. Technol. 36:1923-1930.

Stake, R. E. (1988). The art of case study research, Thousand Oaks: Sage Publications.

Strang, V. (2006). Integrating the social and natural sciences in environmental research: a discussion paper. *Environment, Development and Sustainability*, 11(1), 1-18.

Strauss, A. and Corbin, J. (1990). Basics of Qualitative Research: Grounded Theory Procedures and Techniques. Newbury Park: Sage.

Strauss, I., Corbin, M. C. (1997). Choosing qualitative research: A primer for technology education researchers.

Stuart M., Lapworth D, Crane E, Hart, A. (2012). Review of risk from potential emerging contaminants in UK groundwater. Sci. Total Environ. 416:1-21

Stuart, M., Reeder, D. (2008). Review of risk from potential emerging contaminants in UK groundwater. Science of the Total Environment, 416, 1–21

Stumm, W., Morgan, J. I. (1981). Aquatic chemistry: an introduction emphasizing chemical equilibria in natural waters. New York: Wiley-Interscience, 780 p.

Subramanian, L., & Siromony, P. M. V. (2014). Drinking water issues in Rural India: Need for stakeholders' participation in Water resources management. Future of Food: Journal on Food, Agriculture and Society, 2(1), 93-110.

Tabor, G. M. (2001). Conservation biology and the health sciences. Conservation biology: research priorities for the next decade, 155-173.

Taher, T. Bruns, B., Bamaga O., Al-Weshali A., & van Steenberg F. (2012). Local groundwater governance in Yemen: building on traditions and enabling communities to craft new rules. Hydrogeology Journal. 20, (6) pp. 1177-1188

Takounjou, A. F., Kuitcha, D., Fantong, W. Y., Ewodo, M. G., Haris, H. K., & Issa, T. O. (2013). Assessing groundwater nitrate pollution in Yaoundé, Cameroon: modelling approach. World Applied Sciences Journal, 23(3), 333-344.

Templeton, M. R., Hammoud, A. S., Butler, A. P., Braun, L., Foucher, J. A., Grossmann, J., ... & Jourda, J. P. (2015). Nitrate pollution of groundwater by pit latrines in developing countries.

Tewari, D. D. (2009) A brief historical analysis of water rights in South Africa. Water Int. 30 (4) 438-445.

The Environment Agency, (2009). Environmental Permitting Guidance on Groundwater Activities (England and Wales) Regulations 2010, version 1.0.

The Environment Agency, (2012). Groundwater Protection Principles and Practise (GP3) LIT 7562, version 1.

Tindimugaya, C. (2010) Assessment of groundwater availability and its current and potential use and impacts in Uganda. Country Report prepared for project: Groundwater in Sub-Saharan Africa: Implications for food security and livelihoods' International Water Management Institute, Sri Lanka.

Todd, K. (1980). Groundwater Hydrology. Published by John Wiley & Sons, New York Chichester, - 2nd Edition.

Tran, N. H., Hu, J., Li, J., & Ong, S. L. (2014). Suitability of artificial sweeteners as indicators of raw wastewater contamination in surface water and groundwater. *Water research*, 48, 443-456.

Tredoux G, Cave L, Engelbrecht P. (2004). Groundwater pollution: Are we monitoring appropriate parameters? *Water SA* 30(5): 114–119.

Tredoux, G. (2003). Nitrate and associated hazard quantification and strategies for protecting rural water supplies. Water Research Commission.

Trick, J.K., Stuart, M., & Reeder, S. (2008). Contaminated groundwater sampling and quality control of water analyses. *Environmental geochemistry site characterization, data analysis and case histories*. Elsevier, London, 29-57.

U.S. Environmental Protection Agency, (2010). Ground Water Sampling-A Workshop Summary, Dallas, Texas, November 30-December 2, EPA/600/R- 94/025, 146 pp.

UNDP (United Nations Development Programme) (2012). The Rise of the South: Human Progress in a Diverse World. New York, UNDP.

United Nations Development Programme, (2000). World Resources 2000-2001. Washington DC, World Resources Institute

United Nations Environment Programme, (1989). Environmental Data Report 1989/90, Blackwell Reference, Oxford, 547 pp.

United Nations Environment Programme, (1996). Groundwater: a threatened resource. UNEP Environment Library, No.15. (Nairobi, Kenya: UNEP.)

United Nations Population Division, (2001). World Population Prospects 1950-2050 (The 2000 Revision). New York, United Nations.

United Nations, (2012). Review of the contributions of the MDG Agenda to foster development: Lessons for the post-2015 UN development agenda. UN System Task Team on the Post-2015 UN Development Agenda. New York, UN.

United Nations, (2015). The United Nations World Water Development Report 2015: Water for a Sustainable World. Paris, UNESCO.

United States Environment Protection Agency, (2001). Risk Assessment Guidelines for Superfund (RAGS), vol. 1, part D, US Government Printing office, Washington, DC.

United States Environment Protection Agency, (2002). Risk Assessment Guidelines for Superfund (RAGS), vol. 1, part E, US Government Printing office, Washington, DC.

United States Environmental Protection Agency, (2010) Pavillion Groundwater Superfund Site Assessment, Pavillion, Fremont County, Wyoming.

United States Environmental Protection Agency, (2011). *National Menu of Best Management Practices for Storm Water Phase II*, United States Environmental Protection Agency[on-line] Available: <http://www.epa.gov/npdes/menuofbmps/menu.htm>. [17/12/2011].

United States Geological Survey Agency (2010) Nutrients in the Nation's streams and Groundwater: National Findings and Implications, Fact sheet 2010–3078.

USAID (2009). *Nigeria: Water and Sanitation Profile*. [Online] Available: http://pdf.usaid.gov/pdf_docs/PNADO937.pdf [12/01/2013].

USEPA. (2013). Methods for Chemical Analysis of Water and Wastes. EPA-600/4-79- 020, USEPA-EMSL, Cincinnati, Ohio 45269, March.

Van Genuchten, M. T, Simunek, J., & Sejna, M. (2005). The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. University of California-Riverside Research Reports, 3, 1-240.

Van Lanen, H. A. J. (1999). Monitoring for groundwater development in arid regions. International conference on on regional aquifer system in arid zones. Managing non-renewable resources in Tripoli (Libya).

Velasquez EV , Creus S , Trigo RV , et al. (2013). Pituitary-ovarian axis during lactational amenorrhoea. II. Longitudinal assessment of serum FSH polymorphism before and after recovery of menstrual cycles. *Hum Reprod*. 21:916–923.

Wada, Y., van Beek, L. P., van Kempen, C. M., Reckman, J. W., Vasak, S., & Bierkens, M. F. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, 37(20).

Wakida, F. T., & Lerner, D. N. (2005). Non-agricultural sources of groundwater nitrate: a review and case study. *Water research*, 39(1), 3-16.

Walsham, G. (1995). The Emergence of Relativism in IS Research. *Information Systems Research*, 6(4), 376-394.

Wang, M., Zhang, L. M., Prosser, J. I., Zheng, Y. M., & He, J. Z. (2009). Altitude ammonia-oxidizing bacteria and archaea in soils of Mount Everest. *FEMS microbiology ecology*, 70(2), 208-217 water. *J Chem Phys* 109:373–384.

Waylen, K. A., Blackstock, K., and Cooksley, S. (2011). Encouraging land-manager contributions to protecting and enhancing the water environment. Policy brief for Scotland. The James Hutton Institute, Aberdeen.

Weinhold, F. (1998). Quantum cluster equilibrium theory of liquids: Illustrative application to

West, S., and Zimmerman, L. (2008). Redoing gender through divorce. *Journal of Social and Personal Relationships*, 25(1), 5-21.

White, I., and Howe, J. (2003). Planning and the European Union Water Framework Directive. *Journal of Environmental Planning and Management* 46(4):621–631.

WHO (2006). *Protecting Groundwater for Health: Managing the Quality of Drinking-water Sources*. Edited by O. Schmoll, G. Howard, J. Chilton and I. Chorus. ISBN: 1843390795. Published by IWA Publishing, London, UK.

WHO (2011). *Guidelines for drinking-water quality*. 4th ed. WHO Press Geneva, Switzerland. 541p. [Online] Available: www.who.int/water_sanitation_health/publications. [12/11/2013].

WHO and UNICEF (2000). Global Water Supply and Sanitation Assessment 2000 Report. Geneva and New York, World Health Organization and United Nations Children's Fund.

WHO and UNICEF (2014). Progress on drinking water and sanitation: 2014 update. New York, WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation.

Wilson, J. L., and Liu, J. (2004) Backward tracking to find the source of pollution, *Waste Management Risk Remediation*, (1), 181-199.

Wilson, S. (2014). Eyrewell Forest groundwater system investigation.

Winder, N. (2000). Modelling within a thermodynamic framework: a footnote to Sanders (1999). *Cybergeo: European Journal of Geography*.

Wood, W. W. (2013). Guidelines for Collection and Field Analysis of Groundwater Samples for Selected Unstable Constituents. In: U.S. Geological Survey Techniques for Water Resources Investigations, Book 1, and Chapter D-2.

World Bank (2002). Urbanization in developing countries. *The World Bank Research Observer*, 17(1), 89-112.

World Bank (2010). Sociodemographic, urbanisation and Disasters. Washington, DC: World Bank.

World Bank (2012). Managing the Invisible: Understanding and Improving Groundwater Governance.

World Bank, (2000). Strategic Environmental Assessment and Integrated Water Resources Management and Development, the World Bank, Washington D. C.

World Health Organisation (1984). Guidelines for drinking-water quality, health criteria and other supporting information. World Health Organization, Geneva.

World Health Organisation (2011). Guidelines for drinking water quality (4th edn), World Health Organisation.

Wyatt, J. and Wyatt, S. (2003). When and How to Evaluate Health Information Systems? *International Journal of Medical Informatics*, 69, 251-259.

Yaron, B., Dror, I., & Berkowitz, B. (2012). Soil-subsurface change: chemical pollutant impacts. Springer.

Yaron, U., Gammel, P. L., Ramirez, A. P., Huse, D. A., Bishop, D. J., Goldman, A. I., ... & Eskildsen, M. R. (1996). Microscopic coexistence of magnetism and superconductivity in ErNi₂B₂C.

- Yearley, S. (2005). Cultures of environmentalism. *Empirical Studies in Environmental Sociology*.
- Yin, R. K. (2009). Case study research. Design and methods. Thousand Oaks, CA: Sage.
- Yin, R. K., (1994). Case Study Research: Design and Methods. Sage Publications, Thousand Oaks, California.
- Young, C. P., Blackmore, K. M., Reynolds, P. J. and Leavans, A. (1999). Pollution Potential of Cemeteries. Water Research Center R&D. Project Record P2/024/1 for the Environment Agency. 105.
- Younger, P. L. (2007). Groundwater in the Environment. Blackwell publishing, London.
- Zapozec, A. (1994). Guidebook on mapping groundwater vulnerability. IAH (International contributions to hydrogeology). Verlag Heinz Heise, Hannover
- Zekster, A., and Everett, I. (2004). Groundwater Resources of the World and their Use. UNESCO, IHP-VI Series in Groundwater No 6.
- Zheng, C., & Kinzelbach, W. (2000). Calibration of a regional groundwater flow model using environmental isotope data. In Tracers and Modelling in Hydrogeology: TraM'2000; Proceedings of TraM'2000, the International Conference on Tracers and Modelling in Hydrogeology Held at Liège, Belgium, in May 2000 (No. 262, p. 439). IAHS Press.
- Zheng, C., & Wang, P. P. (1999). MT3DMS: a modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; documentation and user's guide.